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DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

June 1980

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TEST METHOD FOR USE OF CAMBRIDGE PROBE

Study Made by .... Soil Mechanics and Pavement Branch

Under the General Direction of .... R. A. Forsyth

Under the Supervision of .... R. H. Prysock and S. B. P. John

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INTRODUCTION

The Cambridge self-boring pressuremeter is designed to bore into homogeneous clays, peats, or other soft cohesive materials without causing appreciable disturbance. The prime intent is to determine in situ soil properties that cannot be duplicated in the laboratory.

Results from this test method should give soil parameters that are closer to actual in-place values, than do presently accepted laboratory methods.

Some of the parameters that evolve from this test are: pore pressure, peak undrained shear strength, and approximate lateral earth pressures.

OPERATIONAL CONCEPT

This probe essentially consists of a miniature cylindrical tunneling machine that is pushed steadily into the ground. The soil entering the cutting shoe is cut into small pieces by a rotating chopping tool and is then carried to the surface with the help of a flushing fluid which is normally water. The water is pumped down the inside of the cutter drive shaft and up the annular space between the drive shaft and the outer rods (EX casing). A cylindrical membrane fitted over the outside of the instrument can be expanded against the undisturbed soil as in a conventional Menard Pressuremeter test. This membrane, made of adiprene, is protected by an outer flexible stainless steel sheath in some cases. The radial expansion of the membrane is measured at its midpoint by three separate pivoted arms which are kept in contact with the membrane by spring cantilevers. The probe loads the soil radially by inflating the membrane against it using gas pressure.

Electronic readout equipment provides data for a plot of radial strain against applied pressure from which the shear stress/shear strain diagram for the soil is determined by a simple graphical transformation. More than one soil parameter can be obtained from the result of these tests. Schematic diagrams of the Cambridge pressuremeter before insertion and during an expansion test are presented in Figures 1 and 2.

DESCRIPTION OF CAMBRIDGE PROBE AND ITS ACCESSORIES

The Cambridge pressuremeter has two basic functions. The first is to bore into the desired soil stratum and provide a precise cylindrical cavity. This self-tunneling portion of the probe consists of three parts (1):

(a) Cutting shoe (Fig. 3) - cuts cylindrical hole for probe.

(b) Chopping tool (Fig. 3) - grinds soil cuttings and mixes them with water.

(c) Drive shaft - couples the chopping tool to the hydraulic drive unit and carries water to chopping tool.

The second basic function is to measure the various parameters of the soil layer. The measurement facilities consist of:

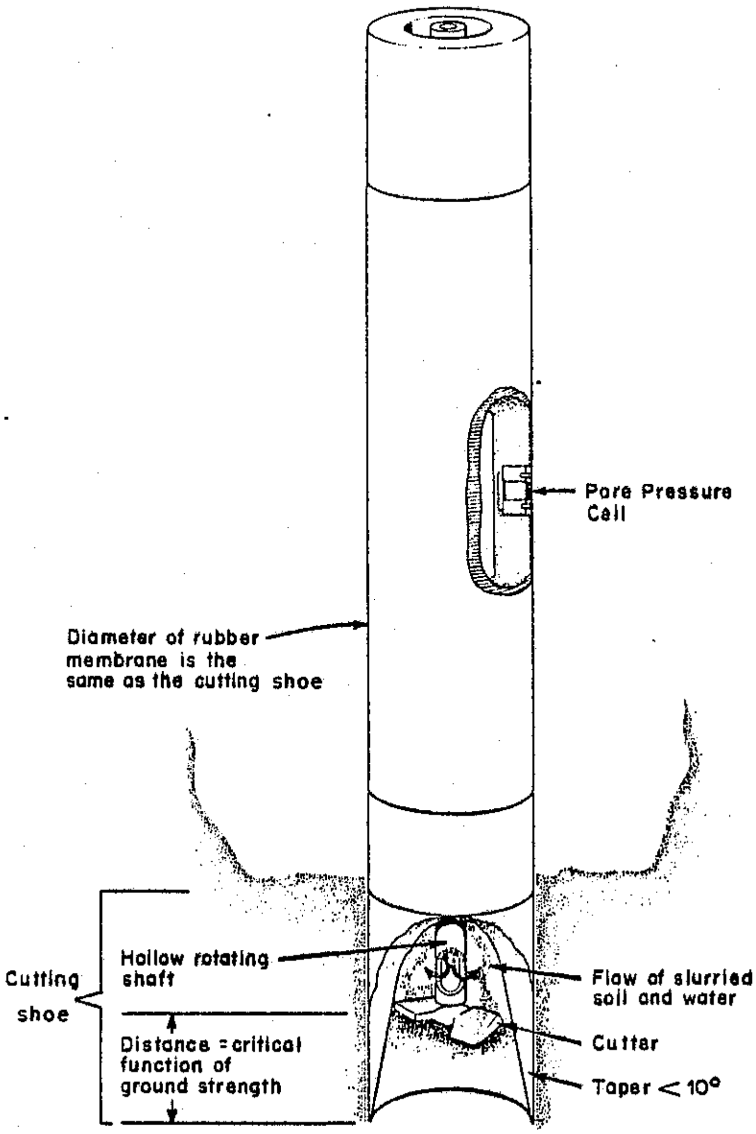


FIGURE 1
BEFORE INSERTION

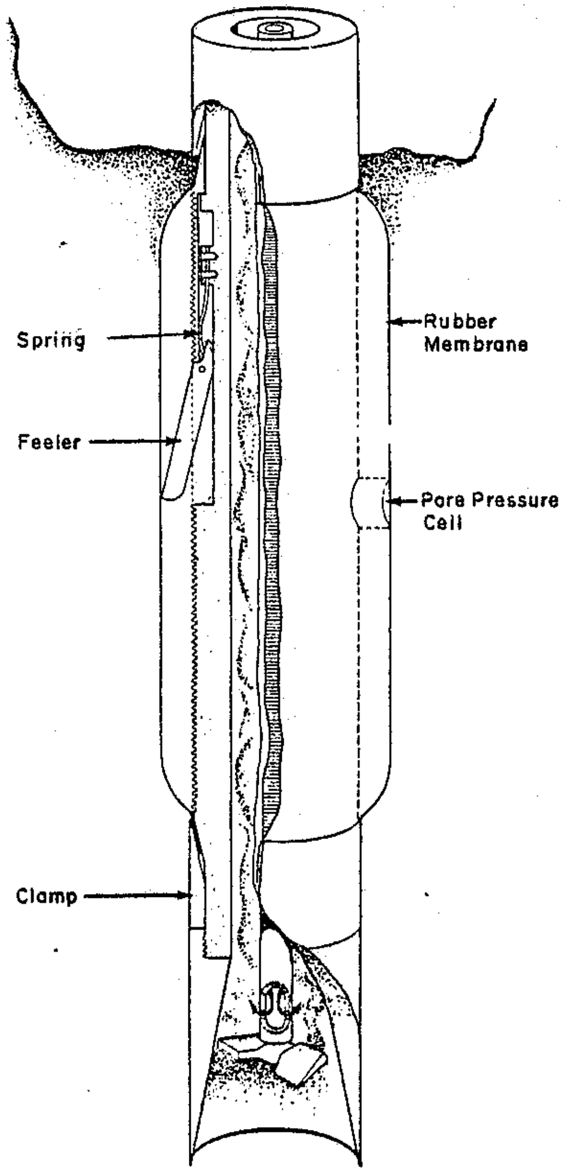


FIGURE 2
DURING AN EXPANSION TEST

CAMBRIDGE SELF-BORING PRESSUREMETER

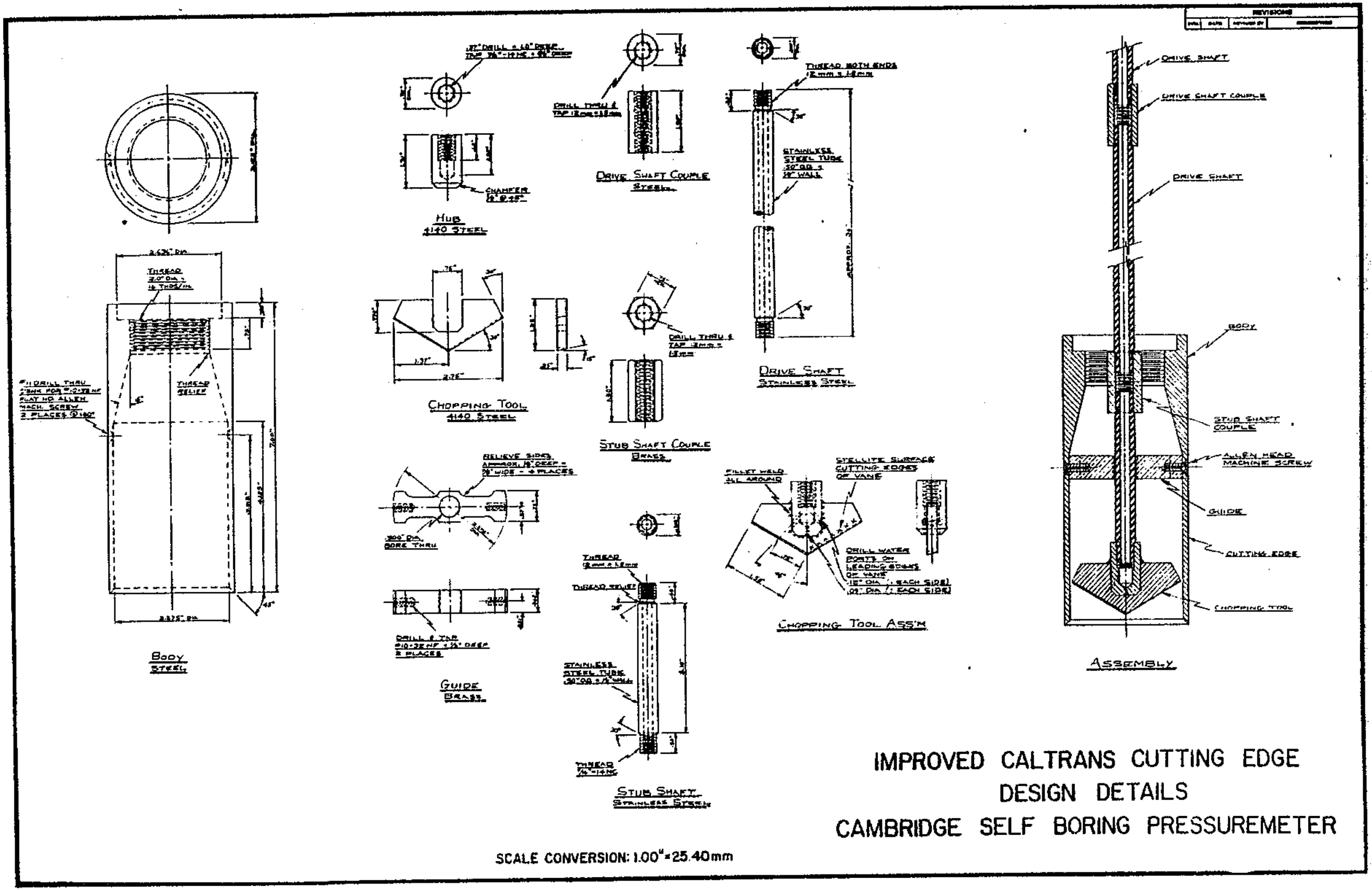

IMPROVED CALTRANS CUTTING EDGE
DESIGN DETAILS
CAMBRIDGE SELF BORING PRESSUREMETER
SCALE CONVERSION: 1.00"=25.40mm
Body
Steel
Hub
4140 Steel
Drive Shaft Couple
Steel
Drive Shaft
Stainless Steel
Chopping Tool
4140 Steel
Stub Shaft Couple
Brass
Guide
Brass
Stub Shaft
Stainless Steel
Chopping Tool Ass'm
Assembly
Drive Shaft
Drive Shaft Couple
Body
Stub Shaft Couple
Allen Head Machine Screw
Guide
Cutting Edge
Chopping Tool

FIGURE 3

(a) Membrane (Fig. 1) - elastic tube (adiprene or latex) which is expanded radially against the soil wall to measure soil strength parameters.

(b) Pore pressure cells (Fig. 1) - two strain gage equipped pressure cells for measuring in situ pore pressure.

(c) Total pressure cell - single pressure cell with strain gage for measuring applied gas pressure within the probe.

(d) Radial strain arms (Fig. 2) - three spring-loaded arms designed to measure the soil deformation. They follow the radial expansion of the membrane and are equipped with strain gages.

A 30.5 meter length of coaxial tubing is used as an interface between the probe and the surface readout equipment. This tubing transmits gas from a bottle of compressed nitrogen (on the ground surface) to the probe. It also houses the electronic cable for connecting the probe's circuits to the 'bodge' box. Also, as a precautionary measure, the tubing is reinforced by a stainless steel safety cable which is fastened to the probe and tied along the length of the coaxial tubing.

Other accessories include the following:

1. EX Casing - connects probe to drilling apparatus (drill rig). Transmits cutting slurry to surface and houses drive shaft. Used also to exert pressure on probe for self-boring process or to pull probe up to surface.

2. Cutter drive unit (Figs. 4 and 5) - mounts on top of chuck assembly of drill rig. Utilizes hydraulic pressure from drill rig to turn drive shaft to probe (TransLab designed and manufactured).

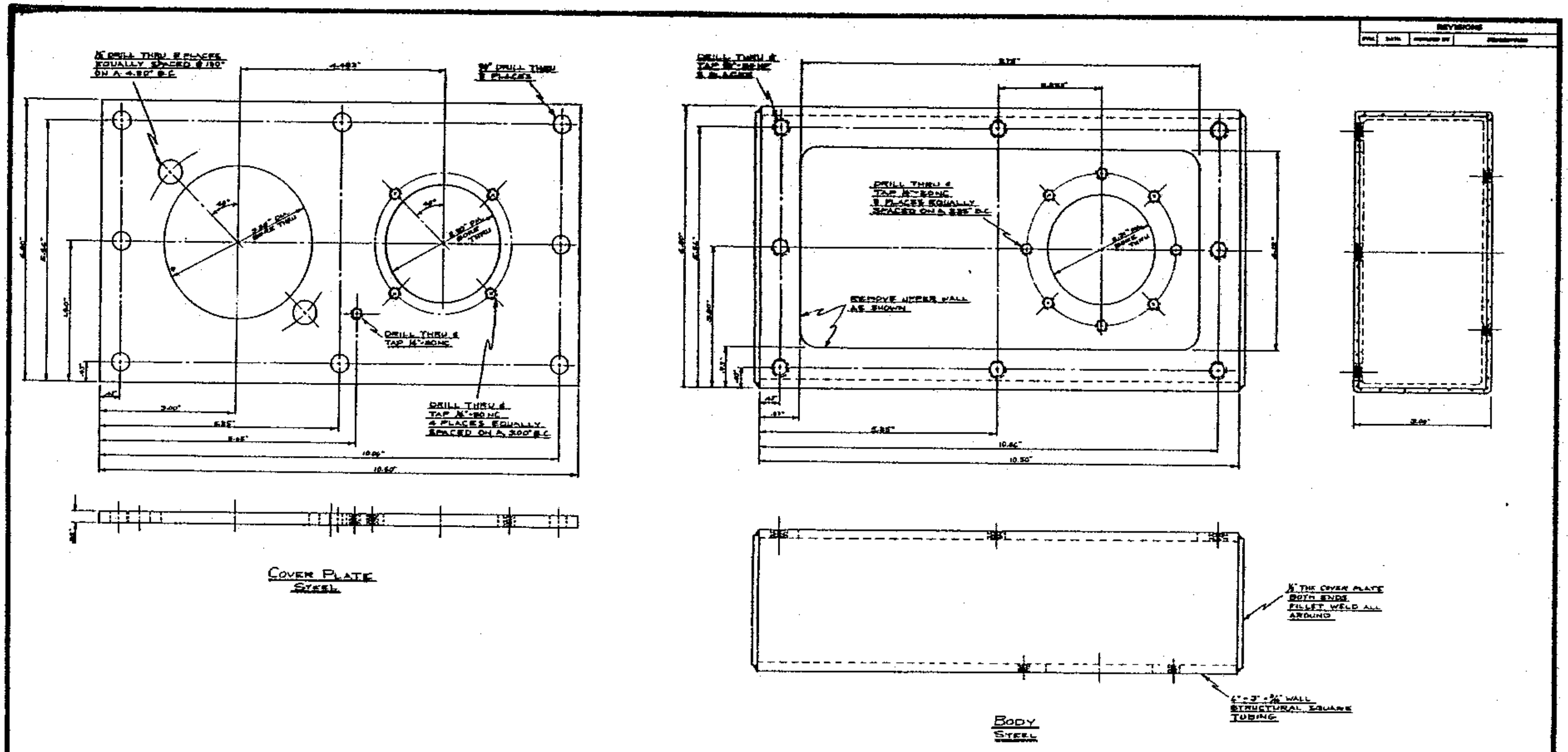
3. 'Bodge' box - cast aluminum box which contains the bridge circuits, switches and connectors for the probe's sensors. Interfaces between the probe and output recording or reading devices (i.e. plotter).

4. Pressure control unit (Fig. 6) - distributes high pressure gas or vacuum to the probe. It has high and low pressure gauges for monitoring gas pressure and a combination vacuum/pressure gauge for monitoring vacuum. There is a manually operated regulator for varying the gas pressure. The unit has quick-connect couplers for the input and output tubing. It was designed and built by TransLab employees.

A gas cylinder is required to carry the gas under pressure. For safety the cylinder should be secured to the vehicle which carries it.

5. X-Y-Y Plotter - A two pen recorder using strain as the abscissa for both pens and total pressure as the ordinate for one pen and effective pressure for the ordinate on the other pen. The plotter receives signals through the 'bodge' box.

6. DVM - Digital Voltmeter; actually a multimeter used to monitor signals from probe via the 'bodge' box. The signals are read in millivolts (2).

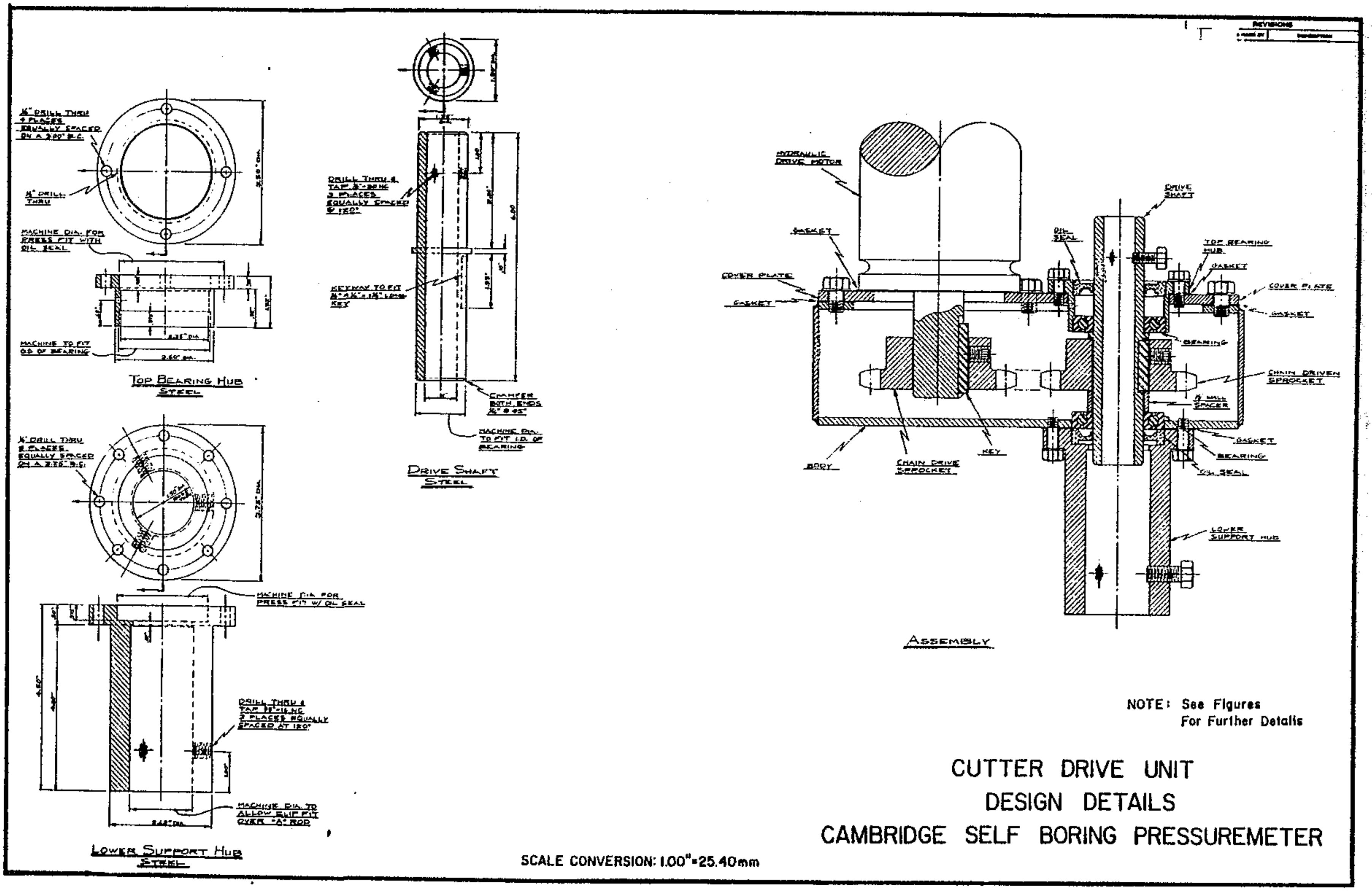


NOTE: See Figures
For Further Details

CUTTER DRIVE UNIT
DESIGN DETAILS
CAMBRIDGE SELF BORING PRESSUREMETER

SCALE CONVERSION: 1.00"=25.40mm

FIGURE 4



TOP BEARING HUB
STEEL
DRIVE SHAFT
STEEL
LOWER SUPPORT HUB
STEEL
HYDRAULIC DRIVE MOTOR
GASKET
COVER PLATE
BODY
CHAIN DRIVE SPROCKET
KEY
DRIVE SHAFT
OIL SEAL
TOP BEARING HUB
BEARING
CHAIN DRIVEN SPROCKET
LOWER SUPPORT HUB
ASSEMBLY
NOTE: See Figures
For Further Details
CUTTER DRIVE UNIT
DESIGN DETAILS
CAMBRIDGE SELF BORING PRESSUREMETER
SCALE CONVERSION: 1.00"=25.40mm

FIGURE 5

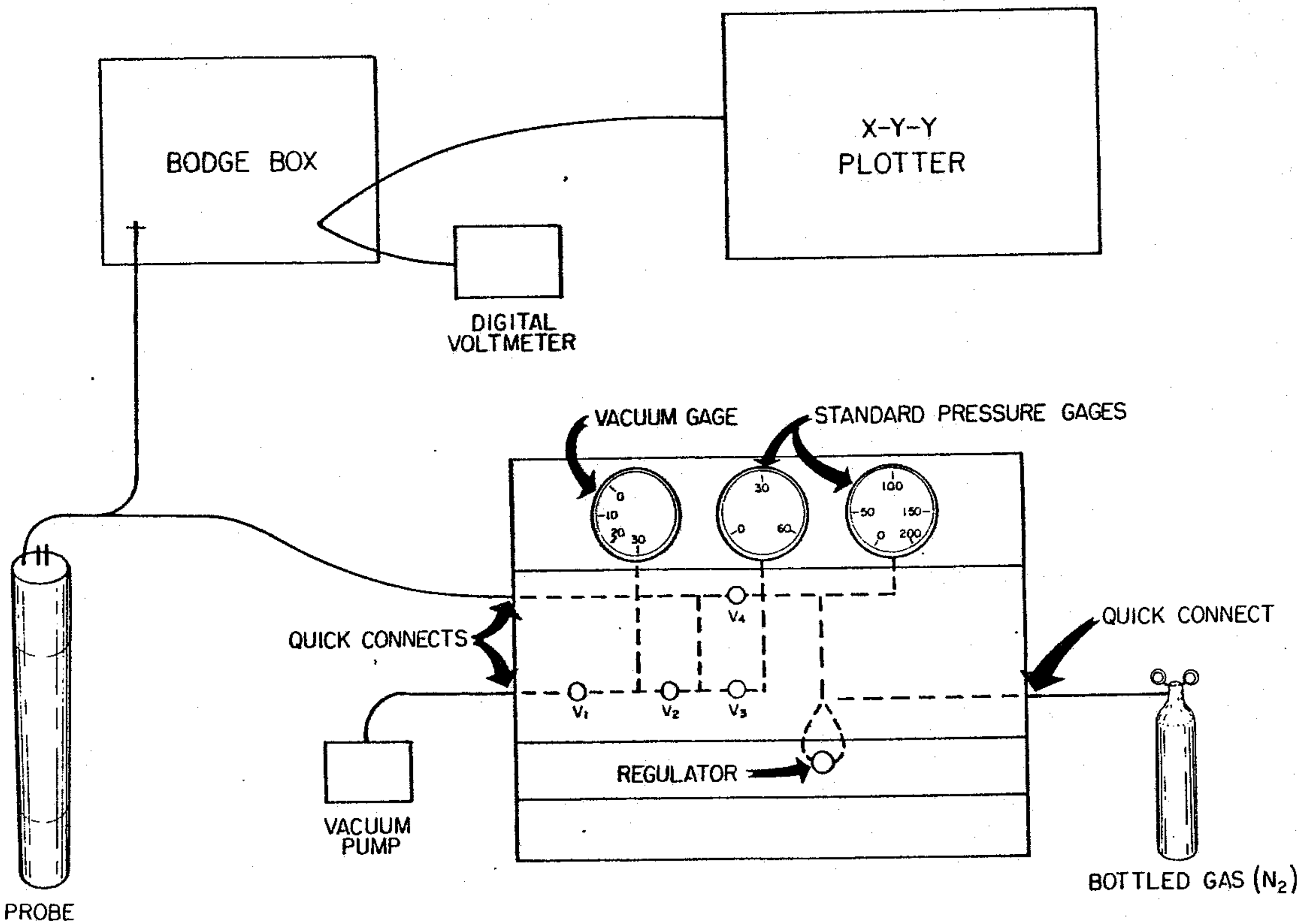


FIGURE 6, INTERNAL SET UP OF CALTRANS CONSOLE

7. Drill rig - A Concore Model N69. This unit is trailer-mounted and is hydraulically operated. It provides the hydraulic drive and the downward thrust for the probe. It also has a pump for delivering water or cutting fluid to the probe's chopping tool.

MODIFICATION AND ADAPTATION

The manufacturer recommends the use of a "hydraulic ground frame" for insertion of the Cambridge self-boring pressuremeter. However, TransLab had the use of a light-duty drill rig with hydraulic capability, necessary for the task.

The drill rig, Concore model N69, is manufactured by Concore Drills, Inc. and is one of a series of Concore rigs used by Caltrans' Office of Structures for subsurface investigation. The N69 is trailer-mounted with a hydraulic system which operates leveling outriggers and the down feed mechanism. The rig was also equipped with a circulating pump which was very important for use of the in situ probe.

The hydraulic system had to be slightly modified to adapt the cutter drive unit (Figs. 4 and 5) to the pressuremeter. This was accomplished by installing valves to divert pressure to the drive unit and return.

For mounting the cutter drive unit, a section of 'A' rod was used. The rod was inserted and clamped in the hydraulic chuck and then the cutter drive was slipped over the rod and clamped to it. An adapter for 1-1/2" galvanized pipe was welded to the bottom end of this 'A' rod.

The outlet for return water was built from two short sections (6") of 1-1/2" galvanized pipe with a tee coupled between. Bronze bushings were brazed inside the galvanized pipe for stabilizing the drive rod. Two pipe unions were incorporated for ease of removal. This assembly was threaded into the adapter at the end of the 'A' rod.

For coupling to the EX casing, an adapter was made with 1-1/2" pipe threads at one end and EX thread at the other. With the EX casing adapter threaded to the bottom of the tee outlet assembly, addition of the 5' drive rod and casing sections was accomplished without necessitating the removal of the cutter drive unit.

In order to distribute the pressure from the bottle of compressed nitrogen to the probe, it was convenient to build a system of valves and gauges so the process could be more completely controlled. This system was also designed so a vacuum pump could be incorporated for holding the membrane tightly against the probe's body while the self-boring process is underway.

After some relatively unsuccessful attempts at self-boring, it was decided that part of the problem had to do with the relative ease with which the bore of the cutting shoe became plugged. One of TransLab's drilling personnel submitted a design for a new cutting shoe (Fig. 3). It had a longer body with a larger throat giving less restriction to flow. Also, he designed a new cutting tool for improved cutting and mixing. This combination, plus added experience, proved fairly successful.

A weakness in the stainless steel drive rod coupler (at the cutting tool) was causing failure under shock loading (i.e. hard objects struck by the rotating cutting tool). This problem was solved by TransLab's machine shop personnel who machined a replacement with improved section modulus.

The rotating joint which was used as a water swivel for much of the testing proved to be inadequate. The drillers suggested the use of a standard, small (3/4") swivel, reduced down to 3/8" as needed.

JOB COORDINATION WITH DRILLING PERSONNEL

The project assistant is responsible for the logistics of a job and must catalog the tools, equipment and any other items necessary to complete the operation. The assistant must determine that the equipment is available and then is loaded into the proper vehicles. The assistant must also coordinate with the drilling personnel as to scheduling of the vehicles to be used and what personnel will be available for the job.

The success of in situ tests with self-boring devices depends on close cooperation between field technicians and drilling personnel. The project assistant is responsible for the test, how the self-boring is to be conducted, and where and when to test. However, he should be open to suggestions from the drillers, especially with regard to the self-boring process. In this respect it is very important that the drilling personnel are aware of the importance of the self-boring concept and it should be reflected in their practice.

CALIBRATION

There are basically two stages in the calibration of the Cambridge pressuremeter (3). The first stage is usually done in the laboratory and involves the strain measuring equipment. The second stage is for developing calibration curves (total and effective pressure) for the membrane being used and may be performed either in the laboratory or the field. This second stage involves the total pressure and pore pressure cells.

Strain Calibration

First, the probe is set up in a horizontal position on V-blocks without a membrane. The radial arms are free to extend. Locking two arms in the closed position with screws, the third arm is extended while its radial extension is being measured electrically and mechanically (see Fig. 7). Mechanical measurements are made with a dial indicator to the nearest 1/100 of an inch. Electrical measurements are made with a digital voltmeter, via the strain position on the 'bodge' box, to the nearest 1/1000 of a volt. The arm is extended in increments of .05" while corresponding voltages are recorded from the digital voltmeter (DVM). The procedure is repeated for all three arms. Then the sum of the voltages for the three arms is tabulated for each .05" incremental movement and the average inch/volt is calculated; giving the multiplication factor for strain, i.e., voltmeter reading x multiplication factor = radial strain in inches.

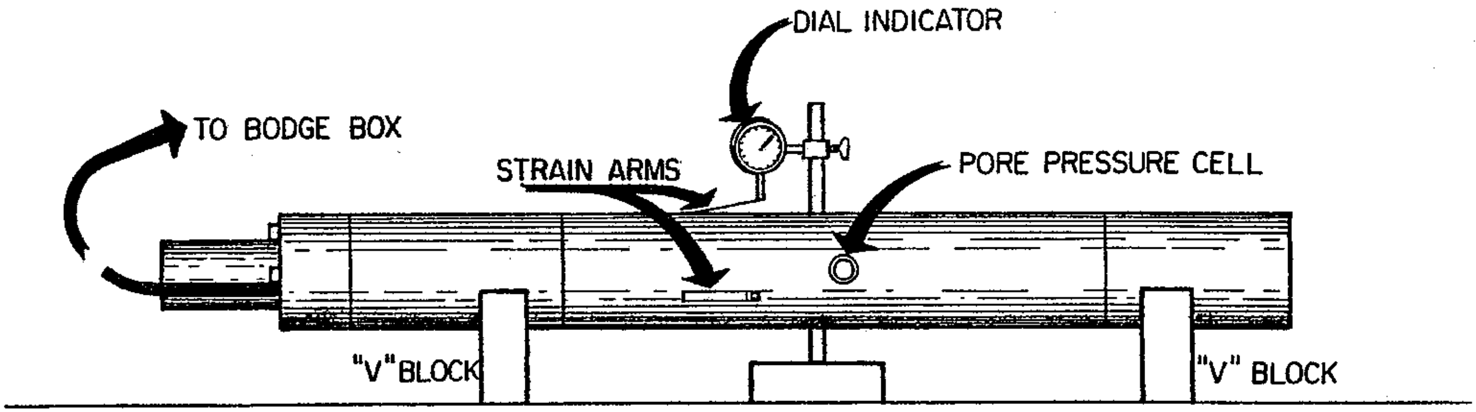


FIGURE 7, LABORATORY CALIBRATION OF RADIAL (STRAIN) ARMS

Pressure Cell Calibration

With the membrane in place (see 'Replacement of Rubber Membrane'), position short sections of extra membrane or large rubber bands at both ends of the membrane to serve as seals between the membrane and calibration tube. Slide the calibration tube over the probe, and secure the probe in an upright position. The tube should be positioned so the two holes in the sides of the tube are aligned with the pore pressure cells thus exposing them to atmospheric pressure.

After making the electrical connections for the plotter and DVM, connect the probe to the pressure supply and excercise the cells at least twice through the entire working pressure range. The procedure for applying pressure is basically the same for testing and calibrating and is as follows: Make sure the system regulator adjusting screw is backed off for zero pressure. Check gas bottle gauges to insure that no pressure exists in the line. Attach input line (from bottle) to pressure distribution box (in this case by coupling quick-disconnect). Attach output line (to probe) to pressure distribution box. Open the gas bottle valve. Adjust bottle regulator pressure for maximum pressure to be used in test. Close valve V2 and open valves V3 and V4. Then record the zero readings of each circuit - strain, total stress and effective stress (see page for procedure) and using small increments of pressure (via the system regulator), inflate the membrane to its required maximum while recording the total and effective stress readings at each pressure increment (see Figs. 8A and 8B). The X-Y-Y plotter will simultaneously

CAMBRIDGE SELF-BORING PRESSUREMETER

Date	Site No.	Hole No.	Test No.	Depth	Water Table	Test Type	Crew
10/30/79	—	—	—	—	—	Cal.	Leech
Calibration Data — No Gas Pressure in membrane							Macfarlane

Total Press.	Strain (mv.)			Eff. Press. (mv)		Scale:
TPC (mv)	Arm 1	Arm 2	Arm 3	PPC-A	PPC-B	Total Press. Eff. Press. Strain
CAL → .205	.437	.447	.441	.683	.742	
ZERO → .002	.018			.064		

Relaxation			
Time	Total Press.	Strain	Eff. Press.

Remarks

Laboratory calibration

polyurethane membrane

FIGURE 8A

CAMBRIDGE SELF-BORING PRESSUREMETER

Test Reading (mv)				Test Reading (mv)			
PSI	Total Press.	Strain	Eff. Press.	PSI	Total Press.	Strain	Eff. Press.
0	.002	.018	.064	50	.192	.412	.440
1	.011	.019	.079	40	.156	✓	.372
2	.015	.026	.088	30	.121	✓	.301
3	.019	.259	.096	20	.086	✓	.233
4	.022	.412	.104	10	.050	✓	.163
5	.026	.412	.111	5	.031	✓	.127
6	.029	.412	.119	0	.004	.016	.069
7	.033	✓	.126				
8	.036	✓	.132				
9	.040	✓	.139				
10	.044	✓	.147				
11	.048	✓	.154				
12	.051	✓	.161				
13	.055	✓	.168				
14	.058	✓	.174				
15	.062	✓	.182				
16	.065	✓	.189				
17	.069	✓	.196				
18	.076	✓	.209				
19	.079	✓	.215				
20	.082	✓	.222				
25	.100	✓	.257				
30	.119	✓	.293				
35	.137	✓	.329				
40	.154	✓	.363				
45	.172	✓	.399				
50	.191	✓	.435				
55	.208	✓	.469				
60	.225	✓	.502				

FIGURE 8B

draw a stress-strain curve (Fig. 9). The expanding membrane should touch the sides of the calibration tube, which would be equivalent to 7% radial strain, at 2 psi ± depending on the elasticity of the membrane.

After the maximum pressure has been reached, reverse the procedure and decrease the pressure while reading total and effective stresses on the way down to zero pressure. (When calibrating in the lab, a transducer should be used to more accurately measure applied pressure.)

A multiplication factor for data analysis can be calculated for both total and effective stresses by dividing each pressure increment by its voltage equivalent and determining the average in psi/volts.

Operating the DVM

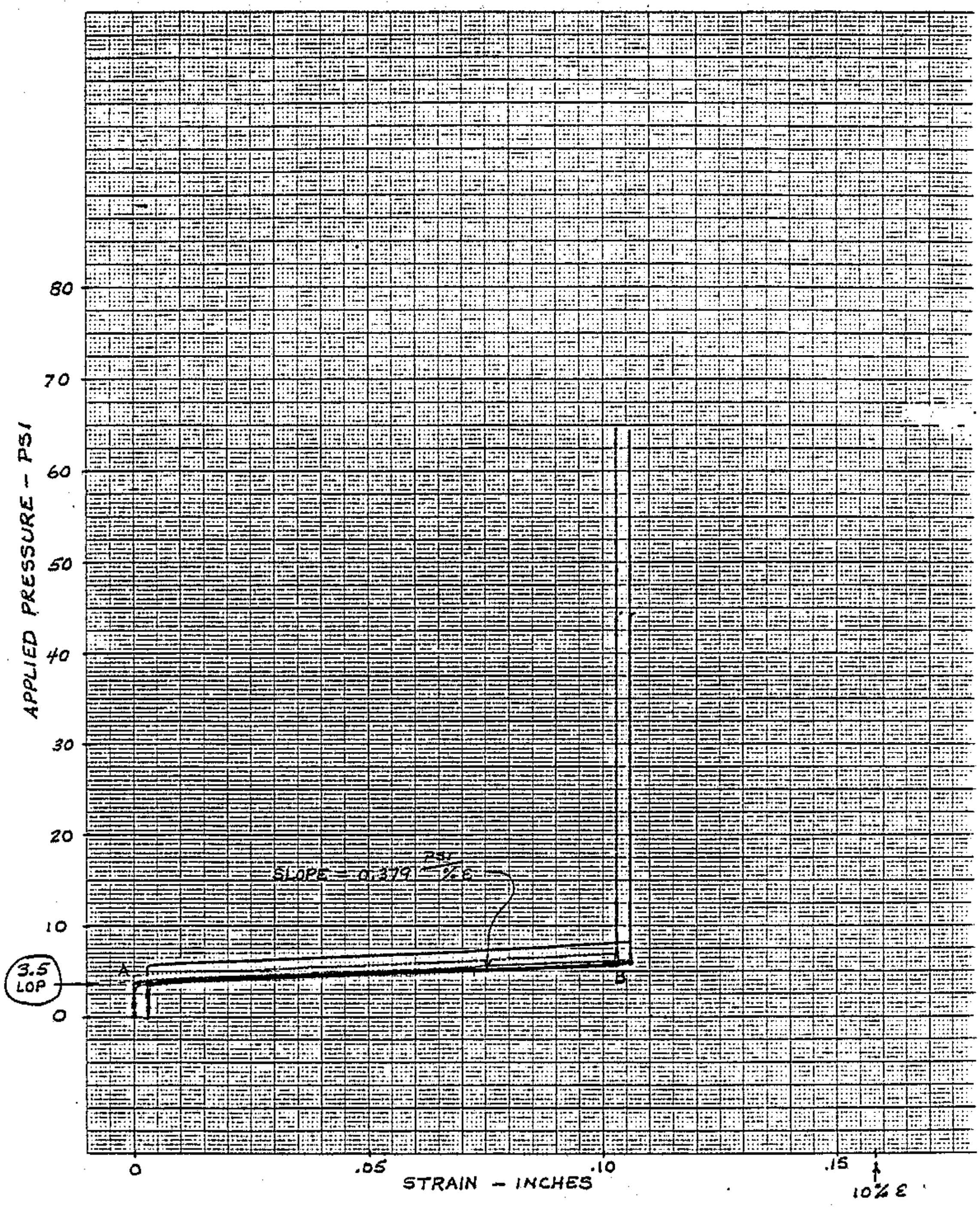
1. Connect pressuremeter to 'bodge' box.

2. Connect battery to 'bodge' box.

3. Connect DVM to 'bodge' box with (with banana connector) at meter connection.

4. Check 9 volt minimum. Record.

5. Check both +5V buss lines as follows: Disconnect banana plug at DVM and use standard probes; read across 'zero' reference and +5V buss (@ bodge box connector board) and then across 'zero' and +5V return from pressuremeter. Record both values.



APPLIED PRESSURE – PSI
80
70
60
50
40
30
20
10
0
3.5 LOP
A
B
SLOPE = 0.379 PSI/%ε
0
.05
.10
.15
10% ε
STRAIN – INCHES

FIGURE 9

6. Reconnect banana plug to DVM and rotate selector switch through the total pressure, effective pressure, and strain positions while recording the zero reading (reference voltage) of each.

7. Hook up resistance box (special double cal-resistor box designed for this pressuremeter) with combination banana plug and alligator clip cable.

8. To read Total Pressure span reference (use TPC resistor 57.9 k), clip onto +5V return (pressuremeter) and +TPC terminal. Switch to Total Pressure with 'bodge' switch. Read DVM and record.

9. To read the two pore pressure span references, use the PPC resistor (17.15 k); leave the clip on the +5V return buss; go across to PPC-A(+) then PPC-B(+). Read and record.

10. To read strain arms 1, 2 and 3, use the PPC resistor; leave the clip on the +5V return and go across to arm 1(+), then arm 2(+) and then arm 3(+). Read and record.

Operating the X-Y-Y Plotter

The X-Y-Y plotter is a very sensitive piece of equipment (3). It cannot tolerate much dust, moisture or vibration and it must have a well-grounded, stable source of 120 volt AC. Since this particular device is to be used in the field where the intolerable is the norm, special care must be exercised to minimize the deleterious effects of the elements.

Use of a mobile lab (i.e., pickup with camper) is important. It keeps the wind, rain and some dust from the plotter. In many cases, however, especially in construction areas, dust is very difficult to eliminate. Therefore, whenever the plotter is not in use, it is very important to replace its dust cover.

Most often a gasoline-powered generator is the only source of power. Since these generators supply ungrounded AC, it is imperative that a proper ground be established. Usually a good ground can be made by driving a commercial type ground rod into the soil a convenient distance from the back of the 'mobile lab'. A wire (say #12 copper) should be attached between the ground rod and the grounding screw of the receptacle box being used. If electrical noise is still present, other steps can be taken to eliminate it such as placing clip-leads between the 'LO' input terminal and the ground (earth) terminal of each of the three axes.

Once the plotter is properly protected from the elements and supplied with a good, stable, power source, it is ready to be "set up".

Set-up procedure is as follows:

1. Set LINE switch to OFF, CHART to RELEASE, SERVO to STANDBY and PEN to LIFT position.

2. Select a convenient range for each axis. (For our use; 25 mv/cm for the X, 25 mv/cm for Y-1 and 5 mv/cm for Y-2.)

3. Set POLARITY switches; +RT for X axis and +UP for Y-1 and Y-2 axes.

4. Position the RESPONSE switches for all three axes to SLOW.

5. Connect input from 'bodge' box to the proper terminals using banana plug connectors. For our use, strain input goes to the X axis, effective pressure to the Y-1 axis and total pressure to the Y-2 axis.

6. Place proper graph paper (HP No. 9270-1024) on the recording platen. Put LINE switch in ON position and CHART to HOLD so that the platen is energized.

7. Install pens. Put the blue pen in the Y-1 holder (bottom) and the red pen in the Y-2 holder (top).

Before recording any tests, the plotter should be 'spanned'. In other words adjust the zero and vernier controls for the proper scale or 'span' within the set range. This is accomplished by the use of a 'dummy load' (or cal-resistor) across the bridge circuit of each mode (i.e., strain) in the 'bodge' box (see procedure for operating the DVM). With the 'dummy load' disconnected (first put SERVO in ON position) set zero at a convenient point on the graph, then clip in the 'dummy load' and set the span with the vernier control. For instance, for strain (X-axis) use arm 3 and adjust vernier until you reach an equivalent of 0.110 inches on the graph [11 cms. actual measurement (0.01" = 1 cm)] with the red pen. Remove the 'dummy load' and recheck the zero. Repeat this procedure with all three axes. Electrical calibration data for the three strain arms, two pore pressure cells and the total pressure cells are summarized below.

Electrical Calibration for Cambridge Pressuremeter
(Laboratory)

	Reading: DVM (Volts)	Reading: Plotter	Calibration Resistance
Strain Arm 1	.0160	0.0"	-
	.4349	.109"	17.15 KΩ
Strain Arm 2	.0161	0.0"	-
	.4455	.1125"	17.15 KΩ
Strain Arm 3	.0161	0.0"	-
	.4393	.110"	17.15 KΩ
Pore Pressure Cell A	.0167	0.0 psi	-
	.6354	89.0 psi	17.15 KΩ
Pore Pressure Cell B	.0167	0.0 psi	-
	.6949	97.4 psi	17.15 KΩ
Total Pressure Cell	.0058	0.0 psi	-
	.2092	57.9 psi	57.983 KΩ

Note: DVM readings may differ from the above depending on conditions but the difference between the zero reading and the reading obtained with the calibration resistor in place should not change appreciably, i.e., total pressure [.2092 MV (w/resistor) -.0058 MV = .2034 MV (.2034 MV should be constant)].

TESTING METHOD

The testing method involves a number of steps as itemized below:

1. Set up the drill rig over the hole and make all the necessary connections to the mud pump from the water supply and mud tank.

2. Connect the probe to the drill rig and to the monitoring system.

3. Prepare the monitoring system by means of which the pressure is applied to the probe and the signals recorded. This would consist not only of the console with valves and gauges designed by Caltrans (Fig. 6) but also the connections to the gas cylinder, the digital multimeter (4) and the X-Y-Y plotter.

4. Connect the vacuum system. This system is necessary to apply the vacuum to the measurement membrane so that while the membrane is being inserted in the hole it will not be damaged by soil particles.

5. Apply the pressure in increments to conduct a constant rate-of-stress test through a system of valves and gauges. As it is understood, various tests including cyclic tests as well as normal expansion tests could be conducted. And finally,

6. Methods of recording test data.

The detailed procedure necessary to accomplish the above mentioned six steps is explained below:

Before the probe is mounted, the drill rig is moved into position. If the surface layer is of an undesirable nature, it should be drilled or augered through using conventional methods. To insure that rocks or any other surface material do not fall in, the hole should be cased through the problem area. The casing should be at least 4" in diameter. It may also be necessary to use drilling mud to lift or remove coarse particles and to keep the hole open.

After the hole has been properly prepared, mount the probe on the drill rig using EX casing. Then, couple the drive rod to the hydraulic cutter drive unit. Next, connect the probe's gas supply line to the pressure system and also make the electrical connection between the probe and the 'bodge' box. If an X-Y-Y plotter is available, hook it to the appropriate jacks on the 'bodge' box; then connect a digital voltmeter to the meter jacks. At this point the operator should set the span on the X-Y-Y plotter and perform the field calibration (see page 22).

A recirculation tank, with a light drill mud, should be incorporated for supplying the fluid for the self-boring process. A mud pump would take the fluid from the tank and force it through a hose, with a water swivel connection at the terminus of the probe's drive shaft, and then through the chopping tool. At this point, the water would mix with the soil cuttings and the resulting slurry would be forced up through the probe and casing, out the swept tee and back into the tank. A screen should be used to keep rocks and other harmful debris from entering the recirculation tank.

At the onset of the self-boring process, evacuate the probe to protect the membrane. A step-by-step procedure for applying the vacuum (Fig. 6) is as follows: Isolate pressure gauges and regulator from the vacuum by closing valves V3 and V4. Open valves V1 and V2. Connect line from vacuum pump. Start pump and set for 5± inches of mercury. (If nonregulating type pump, close valve V1 and turn off pump when 5 inches is attained.) When test depth is reached, immediately release vacuum by opening valve V1 to atmosphere and record values of each circuit. Then monitor and record the pore pressure until it has stabilized (stress relaxation). After a sufficient time for stress relaxation, start the test by turning on the plotter and start increasing gas pressure to the probe in predetermined increments and at a constant rate. While the plotter is drawing the effective and total stress-strain curves, the values from the digital voltmeter may be read and recorded manually for backup or check.

When a cyclic test is desired, the upper and lower limits of the loop should be predetermined and then the pressure can be lowered when the upper limit is reached and then raised when reaching the lower limit (using a constant stress rate).

It should be known in advance that the maximum strain value of the probe's arms is 10% and that value should not be exceeded. At that point of strain the pressure is decreased by a constant rate-of-stress until zero is reached and the test is complete.

REPLACEMENT OF RUBBER MEMBRANE

Occasionally, while using the Cambridge pressuremeter, a membrane becomes torn due to contact with a sharp stone or clam shell and must be replaced. This may be done in the lab or in the field. The following procedure is taken directly from the instruction manual supplied by Cambridge Insitu (3).

1. Begin at the upper end of the machine by removing the cable and gas tube clamp as follows:

   a. Remove the five bolts in the clamp.

   b. The clamp will now come apart into six pieces two of them being retained on the gas tube.

   c. Move the pieces on the gas tube half a metre or so up the tube and remove the other four pieces.

   d. The spacing sleeve is now loose and may be slid up the instrument and off the end.

2. Using the two C spanners provided, undo the ring nut, remove it from its thread and slide it up the instrument and off the end.

3. Slide the tapered upper membrane clamp ring up the instrument and the upper end of the membrane is now free.

4. Grip the upper end of the first cutter drive rod where it protrudes from the top of the instrument and unscrew the cutter from the foot of the instrument. If the instrument is horizontal the first cutter drive rod may be left to lie inside it.

5. Again using the two C spanners provided loosen and remove the cutting shoe.

6. Remove the lower tapered membrane clamp ring.

7. With the membrane still in position, remove the caps of the two pore pressure cells by undoing the screws.

8. Now rotate the instrument so that the two pore pressure cells are horizontal. This is most important as otherwise when the membrane is removed the cells will fall out.

9. The old rubber membrane can now be removed. Great care should be taken not to disturb the covers, top and bottom, over which the membrane passes, nor to allow the pore pressure cells to fall out. It may well be easier to remove the old membrane by cutting it.

10. Take a short piece of old membrane, about 1 cm. Use it as a rubber band to hold the two pore pressure cells in place.

11. Using a pin, remove the small punchings of rubber membrane from the bottoms of the screw holes in the pore pressure cell bodies. See below paragraph 22.

12. Take the fresh membrane and the membrane fitting cylinder. Drop the membrane down the inside of the cylinder and fold its end over the outside at one end of the cylinder.

13. Using a piece of scrap membrane, secure the end of the rubber membrane at the end of the cylinder.

14. Repeat paragraphs 12 and 13 for the other end of the membrane fitting cylinder. Cut off spare membrane taking care not to stretch the membrane inside the cylinder.

15. Using the vacuum pipe, evacuate the space between the inside of the cylinder and the outside of the membrane. It may be necessary to do this more than once before the membrane fits snugly against the inside of the cylinder throughout its whole length, without folds or wrinkles.

16. By clamping, folding the vacuum tube over, or otherwise, retain the vacuum. Slide the membrane, in its cylinder, over the instrument. Remember to remove the band retaining the pore pressure cells.

17. With the membrane properly centered on the instrument, release the vacuum, remove the bands at the end of the membrane and release the membrane from the ends of the cylinder.

18. Trim the membrane to the correct length using a sharp knife. The membrane should be exactly flush with the ends of each of the covers.

19. Replace the upper and lower membrane clamp rings, the shoe and the ring nut and tighten. Do not over-tighten. The 'C' spanners are made the proper length and the proper strength. Their leverage should not be extended by the use of pipes, wrenches and the like. <u>If a good seal is not obtained cut a short length of scrap membrane about 1-1/2 cm and place it over each end of the membrane under the tapered membrane clamping ring. This will increase the clamping pressure on the O ring</u>.

20. Find, by feel, the centre of a pore pressure cell. In the exact centre insert the needle of the hypodermic syringe and lift up the membrane.

21. Cut a very small hole with a scalpel or razor blade. When the stretch in the rubber membrane has been released by the cutting the hole should be 6 mm diameter.

22. Place the cap of the pore pressure cell over the rubber membrane. Drive the cap screws through the membrane and into the body of the pore pressure cell. Let them make their own hole, forcing a small circle of rubber into the bottom of the threaded hole. Tighten the screws fully.

23. Repeat paragraphs 19, 20 and 21 for the pore pressure cell on the opposite side.

Apart from filling the cells with water the instrument is now ready for use again.

OPERATIONAL PROBLEMS

During the early stages of testing, certain problems arose that had to be solved in order to complete the testing program.

As mentioned in the section on X-Y-Y plotters, there was, and still is, a great deal of difficulty using X-Y-Y plotters in the field.

The type of membrane that was originally supplied with the probe was made of soft, thin rubber and was extremely vulnerable to hard, sharp objects including clam shells. In order to combat this problem, a great deal of care was taken to penetrate the hazardous surface layers using casing and drill mud and other precautions to insure that rocks or any other deleterious objects were not present in the hole. A new type of membrane made of a polyurethane is now available and is more resistant to cutting but it is still imperative to start with a clean hole.

In one situation, the soil being tested was a very fibrous, peaty clay. The fibrous material would quickly clog the bore of the probe, necessitating frequent withdrawal for cleanup. This led to the design of a new cutting shoe and tool (see Modification and Adaptation) which greatly improved the situation.

Another problem became evident when boring at extended depths (beyond 10 meters). The membrane had a tendency to pull out of its lower retainer due to adhesion of the clayey soils. It was suggested by the supplier of the Cambridge pressuremeter that a vacuum be applied within the membrane, sucking the thin material up tight against the probe. This method showed some success, however, it also changed initial conditions in the probe and caused some questions as to the accuracy of the initial readings.

DEDUCTION OF PARAMETERS

After the pressuremeter field data (Figs. 10A and 10B) has been successfully collected, it must be analyzed to obtain the desired parameters.

The first step in the analysis is to account for the resistance due to the membrane. This is done by using

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SOIL MECHANICS AND PAVEMENT BRANCH

CAMBRIDGE PRESSUREMETER TEST

DATE	SITE NO.	HOLE NO.	TEST NO.	DEPTH	WATER TABLE	TEST TYPE	CREW
11/7/79	Dumbr. Br.	CPM 2	2	20.5	—	N	Leech, Hall, Nunes, Macfarlane

CALIBRATION DATA — NO GAS PRESSURE IN MEMBRANE

TOTAL PRESSURE	STRAIN (mV)			EFFECTIVE PRESSURE	
TPC (mV)	ARM 1	ARM 2	ARM 3	PPC — A	PPC — B
Cal. .212	.467	.482	.472	.603	.662
Zero .010	.040			.085	

SCALE: TOTAL PRESS. 5 mV/cm; EFF. PRESS. STRAIN } 25 mV/cm

RELAXATION			
TIME	TOTAL PRESSURE	STRAIN	EFF. PRESSURE
0923	.006	.044	-.018
0925	✓	✓	-.026
0927	✓	✓	-.025
0929	.007	.041	✓
0933	✓	✓	-.026
0943	.006	.043	-.028
0953	.009	.042	-.020

REMARKS

Start — 0850
Stop (add rod 0854
Start 0914
Cutter Set Back = 1/4"

FIGURE 10 A, TYPICAL CAMBRIDGE PRESSUREMETER TEST SHEET.

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SOIL MECHANICS AND PAVEMENT BRANCH

CAMBRIDGE SELF-BORING PRESSURMETER TEST SHEET — DATE: 11/7/79

TEST READING				TEST READING			
PSI	TOTAL PRESSURE	STRAIN	EFFECTIVE PRESSURE	PSI	TOTAL PRESSURE	STRAIN	EFFECTIVE PRESSURE
0	.009	.042	−.020	15	.070	.358	.081
1	.015	✓	−.007	10	.050	.088	.071
2	.020	✓	−.001	5	.034	.042	.041
3	.023	✓	+.007	0	.008	.044	−.008
4	.027	✓	+.011	Time —	1007±		
5	.030	✓	.021				
6	.034	.043	.026				
7	.037	.044	.035				
8	.042	✓	.040				
9	.045	.045	.049				
10	.048	✓	.054				
11	.052	✓	.062				
12	.056	✓	.067				
13	.059	✓	.077				
14	.064	.047	.083				
15	.067	.054	.091				
16	.071	.068	.096				
17	.074	.092	.104				
18	.079	.125	.109				
19	.081	.160	.114				
20	.086	.200	.119				
21	.087	.259	.124				
22	.092	.333	.128				
23	.096	.415	.136				
24	.100	.532	.141				
23	.095	.622	.130				
22	.092	.605	.127				
21	.090	.589	.118				

FIGURE ~~10~~ B. TYPICAL CAMBRIDGE PRESSUREMETER TEST SHEET.

the calibration data (Figs. 8A, 8B, and 9); more specifically, the curve from the X-Y-Y plotter (Fig. 9). The procedure is explained as follows:

The vertical straight line portion of the curve from the origin to point A (in this case 3.5 psi) represents what is called 'Lift-Off Pressure'. The straight line portion of the curve between points A and B represents a proportional stress-strain relationship of the membrane. To correct for the resistance of the membrane in the field curve, a formula is developed using the 'Lift-Off Pressure' as a constant and the slope of the line between points A and B (0.38 psi/%ε) as a correction factor for strain. Therefore, using this calibration curve, the correction formula would be for any point C on the field curve (Fig. 11):

$$P_{uncorr.}(psi) - (3.5 \text{ psi} + 0.38 \text{ psi}/\%\varepsilon) = P_{corr.}$$

where %ε is the strain at point C.

After the field curve has been corrected, further analyses may be carried out. This may be accomplished by computer or manual methods. The following is a manual method for determining a derived shear stress-strain curve from the corrected field curve.

<u>Graphical Sub-Tangent Method</u>*

Based on the theory of unique shear stress-strain curve discussed by Baguelin, et al (6), Palmer (7), and Ladanyi

*<u>Note</u>: The following methods of analysis are taken from Reference 5.

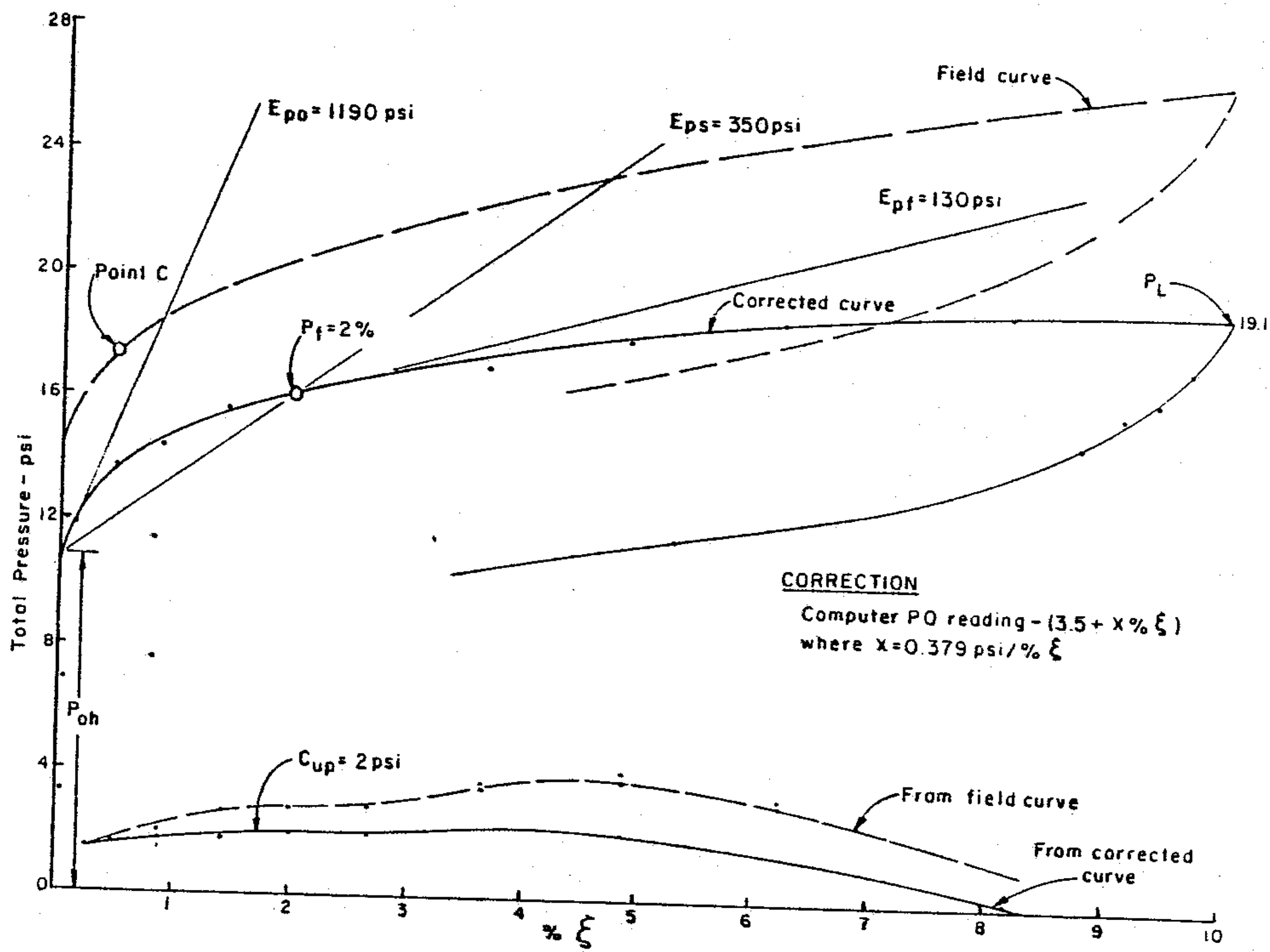


FIGURE 11, TYPICAL CAMBRIDGE PRESSUREMETER TEST PLOTS.

(8), the sub-tangent to any point on the experimental curve is given by

$$\tau_i = \varepsilon_i \ (1+\varepsilon_i).$$

In Figure 12, at Point i, horizontal and vertical lines AB and AE are drawn. A tangent (AC) is drawn at Point i to meet vertical axis at C. BC is the sub-tangent at Point i. The distance BC is plotted vertically below Point i as EF = x = BC. Thus, one point (F) on the derived shear stress-strain curve is obtained. By repeating this process a number of times the entire derived shear stress-strain curve is obtained.

The derived curve by the graphical sub-tangent method is definitely affected by the intervals chosen for drawing the tangents. The smaller the intervals, the more aberrations were seen in the shape; the larger the intervals, the less aberrations.

Geotechnical parameters can be deduced from either the pressuremeter curve, or the derived shear stress-strain curve (derived curve). The following parameters can be deduced from the pressuremeter curve (Fig. 13):

- Total in situ horizontal pressure (P_{oh})

- Practical limit pressure (P_ℓ)

- Theoretical limit pressure (P_L)

- Net practical limit pressure ($P_\ell{}^* = P_\ell - P_{oh}$)

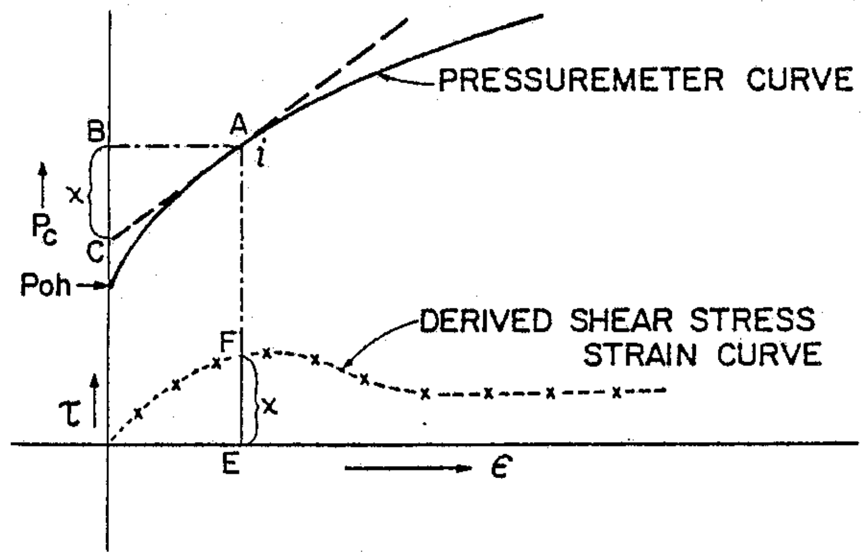


FIGURE 12 GRAPHICAL SUB-TANGENT METHOD

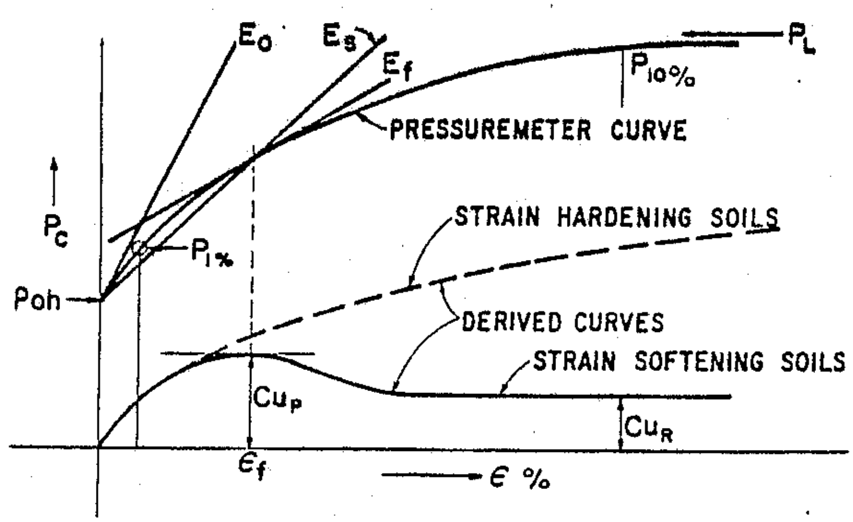


FIGURE 13 DEDUCTION OF GEOTECHNICAL PARAMETERS

- Net theoretical limit pressure ($P_L^* = P_L - P_{oh}$)

- Measured pressure values at various radial strains (P_1, P_{10})

- Pressure at strain of failure (P_f)

- Initial tangent modulus (E_{po})

- Secant modulus (E_{ps})

- Modulus at failure (E_{pf})

- Average undrained shear strength (Cu_{av})

The following parameters can be deduced from the derived shear stress-strain curve:

- Peak undrained shear strength (Cu_p)

- Residual undrained shear strength (Cu_r)

- Initial tangent modulus (E_{do})

- Secant modulus (E_{ds})

- Strain at failure (ε_f)

- Sensitivity (S_t)

The parameters enumerated above are regrouped as follows for the purpose of describing the methods available to determine them.

- Undrained shear strength (Cu_p, Cu_r, Cu_{av}, ε_f)

° Limit pressure (P_ℓ, P_ℓ*, P_L, P_L*)

° Pressure values (P_1, P_{10}, P_f)

° Moduli from pressuremeter curve (E_{po}, E_{ps}, E_{pf})

° Moduli from derived curve (E_{do}, E_{df})

° Coefficient of earth pressure at rest (K_o from P_{oh} value)

° Sensitivity (S_t)

Undrained Shear Strength

Referring to Figure 13, the shear strength values are obtained from the derived curve. The peak shear strength (Cu_p) is measured as the maximum value in the case of strain-softening materials. In the case of strain-hardening materials, there will be no pronounced peak as the curve keeps ascending. The Cu_p value can then be determined from the maximum point of curvature.

The residual shear strength (Cu_r) values are taken as the average of the values for larger strains, in the case of strain-softening materials; and the value corresponding to ε = 10% as Cu_r value, in the case of strain-hardening materials. The strain at failure (ε_f) is taken at the point of strain corresponding to Cu_p.

The parameters Cu_p, Cu_r, and ε_f are based on the unique shear stress-strain curve obtained using the Baguelin-Palmer-Ladanyi Theory (6,7,8).

A semi-empirical (SE) approach can be used to estimate Cu_p. Amar, et al's (9) basic formula using a factor of 5.5 was employed in this analysis:

$$Cu_p = \frac{P_\ell - P_{oh}}{5.5}$$

Where P is the practical limit pressure, and P_{oh} is the total horizontal pressure. (Practical limit pressure is defined later in this chapter.)

Using Gibson and Anderson's (G&A) Theory (10), the corrected pressure values could be plotted against log $[\Delta V/(\Delta V+V_o)]$ values where ΔV is the volume injected into the probe and $\Delta V + V_o$ is the current volume of the probe. V_o is the theoretical initial volume measurement of the module. A typical curve is shown in Figure 14. The initial portion of the curve is curved and the latter portion of the curve is almost a straight line. The slope of the straight line portion is taken to be the average shear strength (Cu_{av}).

$$Cu_{av} = \frac{dP_c}{d\left(\frac{\Delta V}{\Delta V+V_o}\right)}$$

From the unique shear stress-strain curve, Cu values at any corresponding strain can be determined; whereas, in the semi-empirical and the Gibson and Anderson methods, only a single value of Cu is obtained. The ratio Cu_p/Cu_r is defined as the sensitivity of the soil. This value can be calculated only from the unique shear stress-strain curve.

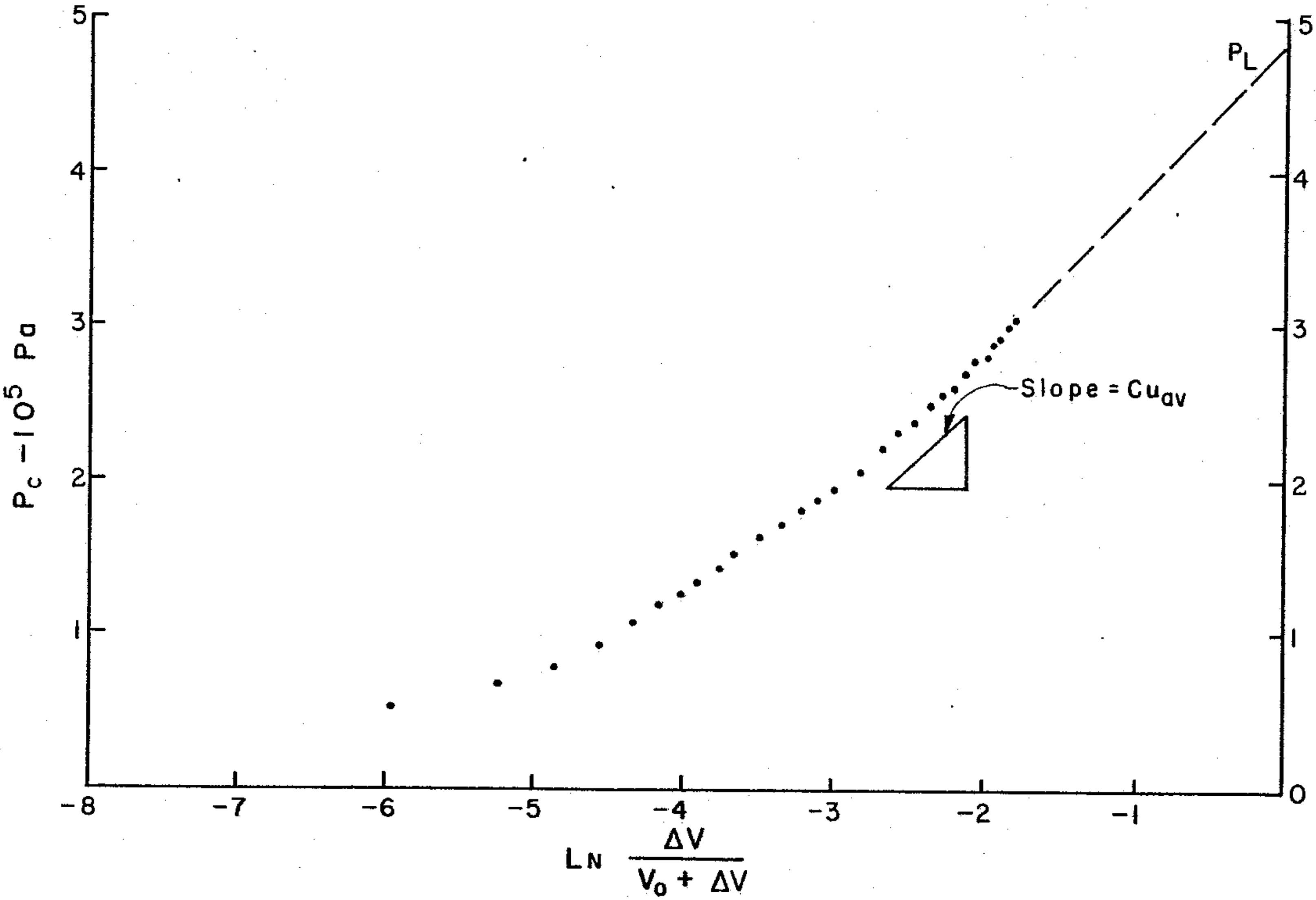


FIGURE 14, TYPICAL PLOT BY GIBSON AND ANDERSON THEORY

Limit Pressure

In the Menard System, limit pressure is the pressure that occurs when the volume of the cavity is doubled. This definition is not used with respect to self-boring pressuremeter procedures. The true limit pressure occurs with infinite expansion of the cavity. This is called the theoretical limit pressure (P_L). In practice, however, infinite expansion cannot be realized. In most cases the tests are run up to strains of about 10% and from these data, limit pressure is estimated.

There are three types of limit pressure used in practice. Baguelin and Jezequel (11) have defined one type as the practical limit pressure, P_ℓ, which is based on experience and varies from soil type to soil type. They have suggested P_ℓ values as follows:

Soil Type	P_ℓ
Clays (soft or stiff)	P_{10}
Loose silts or sands	$1.5\ P_{10}$
Compact sands	$2.0\ P_{10}$

The second type of limit pressure, theoretical limit pressure, P_L, is based on the theory of Gibson and Anderson, and Marsland and Randolph's application thereof (10,12). The pressure value, P_L, obtained when the latter portion of the pressuremeter curve is projected to meet the P_c axis drawn through zero abscissa value (i.e.,

$\frac{\Delta V}{V_o+\Delta V} = 1$, or $Ln(\frac{\Delta V}{V_o+\Delta V}) = 0$) is shown in Fig. 14.

By definition this is equal to an infinite expansion. The value P_L can also be determined by inspection of the pressuremeter curve.

The third type can be defined as the <u>net limit pressure</u>, either P_ℓ^* or P_L^*, and these are equal to $P_\ell - P_{oh}$ (net practical limit pressure) or $P_L - P_{oh}$ (net theoretical limit pressure). Values similar to these have found broad application in foundation design.

In addition to the three described ways of determining P_ℓ and P_L, there are other methods, some of which are here mentioned.

The log-log method was developed by Jezequel, et al (13). Log-log paper is used to plot corrected pressure, P_c, along the vertical axis, and the ratio $\Delta V/V_o$ along the horizontal axis. The final phase usually plots as a straight line. This straight line is prolonged until it meets the vertical axis. The value of P_c at the point of intersection is taken as the theoretical limit pressure.

Van Wambeke and D'Henricourt (14) have developed a method of determining limit pressure, which can be called the inverse curve method. In this method P_c values are plotted versus $1/\Delta V$ values. In their experience the result had three separate, almost straight line portions. The intersection of the third straight line with the vertical axis gives the theoretical limit pressure.

Pressure Values

Other pressure values which are of use in correlation are P_1, P_f and P_{10}. P_1 corresponds to a value of P_c at $\varepsilon = 1\%$; P_{10} corresponds to a value of P_c at $\varepsilon = 10\%$; and P_f corresponds to a value of P_c at strain at failure.

Moduli from Pressuremeter Curve

As shown in Figure 13, initial tangent modulus (E_o), secant modulus (E_s), and tangent modulus at failure (E_f), can be obtained from the pressuremeter curve.

The modulus (E_i) is calculated from the formula:

$$E_i = (1+\nu)\,\frac{\Delta P_c}{\Delta \varepsilon}$$

Where ν = Poisson's ratio, and ΔP_c = value of P_c over a certain strain interval $\Delta\varepsilon$, and $E_i = E_o$, E_s or E_f.

Moduli from Derived Curve

The initial tangent modulus (E_{po}), and secant modulus at failure (E_{ps}), can be calculated from the derived shear stress-strain curve shown in Figure 13, using the same formula described above.

Coefficient of Earth Pressure at Rest

By definition, coefficient of earth pressure at rest, K_o, is the ratio of effective horizontal pressure to effective vertical pressure. A crude estimate of K_o can be obtained from pressuremeter tests as follows:

The effective vertical pressure at any elevation can be calculated from a knowledge of subsurface conditions and unit weights. The pressuremeter measures total horizontal pressure. This value can be very accurately measured if sufficiently long intervals of stress relaxation time are allowed after insertion of the probe to a particular elevation. Usually only short intervals of time are practically possible. Usually 5 to 30 minutes are allowed. From the stress relaxation curve, P_{oh} can be estimated by extrapolation. In clayey soils stress relaxation time can run into many hours, weeks, or months. From this value of P_{oh}, P'_{oh} can be calculated and hence, K_o values.

Sensitivity

Sensitivity, S_t, is defined as the ratio Cu_p/Cu_r; where Cu_p is the peak undrained shear strength, and Cu_r is the residual undrained shear strength. Both these values are determined from the derived curve. This ratio can be easily calculated for strain-softening soils which develop a pronounced peak.

REFERENCES

1. Camkometers, Cambridge Self-Boring Pressuremeters, Descriptive Brochure, Cambridge Insitu Co., Little Eversden, Cambridge CB37He England.

2. Fluke Multimeter, Model 8040A Maintenance Manual, John Fluke Mfg. Co., Inc., P.O. Box 43210, Mountlake Terrace, Washington 98043.

3. Working and Calibration Instructions for Cambridge Self-Boring Pressuremeters, Cambridge Insitu Co., Little Eversden, Cambridge CB37He England.

4. X-Y Recorders Technical Data Brochure, November 1975, Hewlett-Packard Co., 1501 Page Mill Road, Palo Alto, California 94304.

5. John, S.B.P., "French Self-Boring Pressuremeters (PAF68 & PAF72), Vol. II - Instructions for Field Tests, pp 54-67", Report No. FHWA TS-80-209, February 1980.

6. Baguelin, F., Jezequel, J. F., LeMee, E., and Le Mehaute, A., "L'essai d'expansion Cylindrique et la loi Effort Deformation des Sols Purement Coherents", Proc. of the Sixth Inter. Congress on Rheology, Lyon, France, Vol. IV, 1972.

7. Palmer, A. C., "Undrained Plane-Strain Expansion of a Cylindrical Cavity in Clay: A Simple Interpretation of the Pressuremeter Test", Geotechnique, Vol. 22, No. 3, pp 451-457, 1972.

8. Ladanyi, B., "In Situ Determination of Undrained Stress-Strain Behavior of Sensitive Clays with the Pressuremeter", Canadian Geotechnical Journal, Vol. 9, pp 313-319, 1972.

9. Amar, S., Baguelin, F., Jezequel, J. F., and LeMehaute, A., "In Situ Shear Resistance of Clays". Proceedings of the Specialty Conference on In Situ Measurement of Soil Properties, Raleigh, North Carolina, A.S.C.E., Vol 1, 1975 pp 22-46.

10. Gibson, R. E., and Anderson, W. F., "In Situ Measurement of Soil Properties with the Pressuremeter", Civil Engineering and Public Works Review, Vol. 56, No. 658, May 1961, pp 615-618.

11. Baguelin, F., and Jezequel, J. F., "French Self-Boring Pressuremeter (PAF 68, PAF 72, and PAF 76)", Proc. of Symposium on Site Exploration in Soft Ground Using In Situ Techniques, Alexandria, VA., May 1978.

12. Marsland, A. and Randolph, M. F., "Comparison of the Results from Pressuremeter Tests and Large In Situ Plate Tests in London Clay", Geotechnique, Vol 27, No. 2, 1977, pp 217-243.

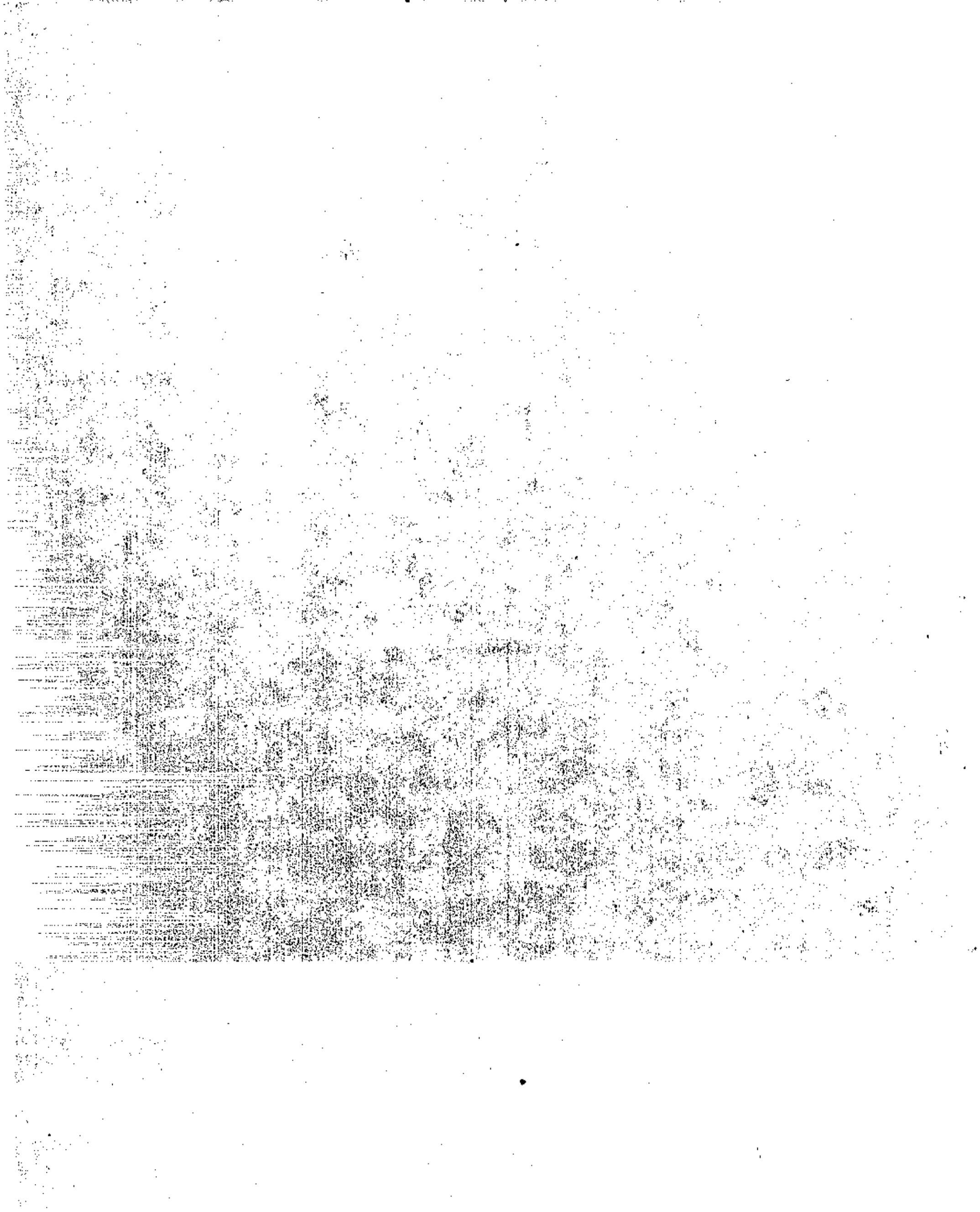
13. Jezequal, J. F., LeMee, E., Saintilan, D., "Exploration de l'essai pressiometrique normal par methode numerique", Bulletin de Liason des Laboratoires des Ponts et Chaussees, No. 69, Janvier-Fevrier 1974, pp 105-114, Ref. 1375.

14. Van Wambeke, A., and D'Henricourt, J., "Courbes Pressiometriques Inverses: Methode d'Interpretation de L'Essai Pressiometrique", Soils-Sols, N. 25 Torne VII, 1975.

Appendix 1

APPARATUS

1. Cambridge Expansion Pressuremeter
2. Bodge Box and Cables w/Banana Plugs
3. X-Y-Y Plotter and Paper
4. Digital Voltmeter (DVM) w/Charger-Adapter
5. Hydraulic Drive Assembly
6. Concore N69 Drill Rig w/Mud Tank
7. Pressure Distribution Box
8. Nitrogen Gas Bottle & Regulator Assembly
9. AC Generator and Extension (50 ft. min.)
10. Vacuum Pump and Tubing
11. Water Swivel and Hoses
12. EX Casing and Drive Shaft Sections w/Couplers
13. Tee and Unions for Cutting Fluid Return
14. Drill Tender w/Water Supply
15. Grounding Rod with Wire
16. Tool Box with Spanners, Hex Keys, etc.
17. Extra Membranes
18. Hypodermic Syringe and Single Edge Razor Blade
19. Stop Watch
20. Instruction Manual
21. Truck
22. 4" Drill Casing



Appendix 2

COMPUTER PROGRAM

The manual method of reducing field data is very time consuming. Therefore, it was advantageous to develop a computer program that would do the work.

The first version, "CAMBR' was designed for inputting 1/2 psi increments of applied pressure with the corresponding total pressure, effective pressure and total strain readings (in mv). The printout consists of tabulated values of the preceding, converted to psi and percent strain and also, calculated values of $\Delta V/V$ and ln $(\Delta V/V)$ (Fig. 15). The program also provides for plotting these values vs % strain or total pressure, including the plotting of total or effective pressure vs % strain and the differentiated total or effective pressure vs % strain curves (Figs. 16, 17, 18 and 19).

As more experience was gained, it was decided that the 1/2 psi increments were unnecessary and were therefore eliminated in favor of 1 psi increments. A modified version of "CAMBR' was created ('CAMBR 2') to take this into account and to improve plotting functions.

To best utilize the plotting aspects of these programs, one should closely observe the tabulated printout. If there are many (more than three) consecutive zero (or near zero) % strain readings, all but the first should be eliminated (Fig. 15). If not, the computer will not be able to differentiate the stress-strain curves. Also one should read the range of pressures from the printout in order to set the limits on the plotter for proper scaling of the curves.

CAMBRIDGE PROBE

CALIFORNIA DEPARTMENT OF TRANSPORTATION
TRANSPORTATION LABORATORY
GEOTECHNICAL SECTION

TEST ID.: 1 JOB NO.: DUMBR-HOLE 2

APPLIED PRESS.	TOTAL PRESS.	% STRAIN	EFFECTIVE PRESSURE	DELTA-V/V		LN(DELTA-V/V)
.00	-.57	.000	-12.74	-.000		-7.818
~~1.00~~	~~1.99~~	~~.000~~	~~-10.59~~	~~-.000~~		~~-7.818~~
2.00	2.85	.000	-9.59	-.000		-7.818
3.00	3.42	.000	-9.02	-.000		-7.818
4.00	3.98	.000	-8.44	-.000		-7.818
5.00	6.26	.000	-6.15	-.000		-7.818
6.00	7.68	.000	-5.15	-.000	DELETE	-7.818
7.00	8.54	.000	-3.86	-.000		-7.818
8.00	9.96	.000	-3.15	-.000		-7.818
9.00	10.53	.000	-2.15	-.000		-7.818
10.00	11.38	.000	-1.43	-.000		-7.818
11.00	12.52	.000	-.14	-.000		-7.818
~~12.00~~	~~13.66~~	~~.149~~	~~.43~~	~~.243~~		~~-1.415~~
13.00	14.51	.531	1.86	.573		-.556
14.00	15.94	.897	2.72	.722		-.326
15.00	16.79	1.478	3.43	.837		-.178
16.00	17.93	2.391	4.15	.913		-.091
17.00	19.07	3.670	5.01	.954		-.047
18.00	20.21	5.730	5.72	.978		-.022
19.00	21.06	8.021	6.30	.988		-.012
18.00	19.92	9.848	4.87	.991		-.009
17.00	19.07	9.466	4.15	.991		-.009
16.00	17.93	8.918	3.15	.990		-.010
15.00	17.08	8.287	2.29	.988		-.012
10.00	11.95	3.753	-.57	.956		-.045
5.00	6.83	-.017	-3.86	-.034		-3.367
.00	.57	-.017	-9.73	-.034		-3.367

Alter data for + values.

More than three 0% strain values causes the program to reject a 'differentiate' command.

The above deleted values are relatively unnecessary.

FIGURE 15

```
100 REM *** CAMBR2***

        ENGLISH PROBE CALCULATION AND PLOTTING PROGRAM.
        MODIFIED 11-30-79     DO NOT USE 1/2 LB. PRESS. READINGS.
110 REM
           ** INPUTS **

120 REM     TES$=   TEST NUMBER
            JOB$=   JOB DESCRIPTION
            NUM =   TOTAL NUMBER OF READINGS
130 REM    ITP=  INITIAL TOTAL PRESS.
           ITS=  INITIAL TOTAL STRAIN
           IEP=  INITIAL EFFECTIVE PRESS.
140 REM     A(1..NUM,1)=  APPLIED PRESS. READINGS.
            A(1..NUM,2)=  TOTAL PRESS. READINGS.
            A(1..NUM,3)=  TOTAL STRAIN READINGS.
            A(1..NUM,4)=  EFFECTIVE PRESS.

150 REM
          ** PROGRAM CALCULATED VARIABLES **
160 REM   TP(1..NUM)=   TOTAL PRESSURE
          TS(1..NUM)=   % STRAIN
          EP(1..NUM)=   EFFECTIVE PRESSURE
170 REM   VOL(X,1) =   V
          VOL(X,2) =   DELTA-V
180 REM   VOL(X,3) =   DELTA-V/V
          VOL(X,4) =   LN(DELTA-V/V)
          VOL(X,5) =   LOG10(DELTA-V/V)
          VOL(X,6) =   LOG10(DELTA-V/V) SCALED -3 CYCLE LOG
190 LF$=CHAR(10)
200 PAG$='PAGE:'
210 R=4.021,V0=2616.9777
220 GOTO 260
230   FOR L=1 TO LF
240   PRINT LF$;
250   NEXT L
260 PRINT;"ENTER DATA FILE NAME ?"
270 INPUT F$
280 PRINT;'SET PERFORATIONS AT TOP OF PRINT HEAD-TYPE CONTINUE'
290 PAUSE
300 LF=68
310 DO 230:250
320 LF,PAGE=1
330 OPEN F$,1,INPUT,OLD
340 INPUT FROM 1:TES$,JOB$
350 INPUT FROM 1:NUM
360 DIM A(NUM,4),TP(NUM),TS(NUM),EP(NUM),AREA(NUM),VOL(NUM,6),DIFF(NUM,4)
370 DIM APR(NUM)
380 INPUT FROM 1:ITP,ITS,IEP
390 MAT INPUT FROM 1:A(NUM,4)
400   FOR X=1 TO NUM
410   TP(X)=(A(X,2)-ITP)*284.6
```

```
420    TS(X)=(A(X,3)-ITS)*.2629*63.17
430    EP(X)=(A(X,4)-IEP)*143.1
440    AREA(X)=PI*((TS(X)*R+R)^2)
450    VOL(X,1)=AREA(X)*51.5
460    VOL(X,2)=VOL(X,1)-VO
470    VOL(X,3)=VOL(X,2)/VOL(X,1)
480    VOL(X,4)=LOG(ABS(VOL(X,3))),VOL(X,5)=LOG10(ABS(VOL(X,3)))
490    NEXT X

500 PRINT IN FORM'28B"CAMBRIDGE PROBE"///':
510 PRINT IN FORM'17B"CALIFORNIA DEPARTMENT OF TRANSPORTATION"//':
520 PRINT IN FORM'24B"TRANSPORTATION LABORATORY"/26B
              "GEOTECHNICAL SECTION"///':
530 PRINT IN FORM'5B"TEST ID.: "15%18B"JOB NO.: "15%///':TES$,JOB$
540 LF=LF+12
550 PRINT IN FORM'3B"APPLIED"5B"TOTAL"8B"%"5B"EFFECTIVE"3B"DELTA-V/V"
              3B"LN(DELTA-V/V)"//':
560 PRINT IN FORM'3B"PRESS."6B"PRESS."5B"STRAIN"3B"PRESSURE"//":
570 LF=LF+3

580    FOR X=1 TO NUM
590 PRINT IN FORM'3B 3%.2% 5B 3%.2% 4B 4%.3% 3B 4%.2% 6B 3%.3% 7B 4%.3%/':
              A(X,1),TP(X),TS(X),EP(X),VOL(X,3),VOL(X,4)

600    LF=LF+1
610    ON LF=58 GOSUB 1570
620    NEXT X


630 DO 1580:1590
640 REM                    **** PLOT ROUTINES  ***
              %STRAIN  VS. TOTAL PRESSURE  -NEW METHOD


650 PRINT IN FORM'5B"PLOT % STRAIN (X AXIS) VS. TOTAL PRESSURE (Y AXIS)"/
              5B"ENTER : XMIN,XMAX,YMIN,YMAX"/':
660 INPUT XMIN,XMAX,YMIN,YMAX
670 PRINT IN FORM'//5B"YOU ENTERED:"/8B5%.%B"FOR XMIN"/8B5%.%B"FOR XMAX"/
          8B5%.%B"FOR YMIN"/8B5%.%B"FOR YMAX"/':XMIN,XMAX,YMIN,YMAX
680 PRINT IN FORM'/5B" OK ANS. YES OR NO"/':
690 INPUT AN$
700 IF AN$='NO' THEN 650
710 PRINT IN FORM'/5B" GET PLOTTER READY THEN TYPE CONTINUE"//':
720 PAUSE
730 H=9999/(XMAX-XMIN),V=9999/(YMAX-YMIN)
740 PRINT:'PLTP'
750   FOR I=1 TO NUM
760   PRINT IN FORM'4%B4%/30(C127)':ROUND((TS(I)-XMIN)*H),ROUND((TP(I)-YMIN)*V
770   NEXT I
780 PRINT'PLTT'
790 REM

      **DIFFERENTIATE STRAIN - T. PRESS. CURVE
        DIFF(1,1..NUM,1)=G(EO) CURVE,DIFF(1,2..NUM,2)=F(EO) CURVE


800 CNT=3,LST=NUM-2
810 MAT DIFF=(0)
820 DIFF(2,1)=TS(2)*((TP(2)-TP(1))/(TS(2)-TS(1)))
830    FOR X=CNT TO LST
840    IF TS(X+2)-TS(X-2)=0     THEN 870
```

```
850     IF TS(X+1)-TS(X-1)=0     THEN 870
860     GOTO 890
870     DIFF(X,1)=0
880     GOTO 900
890     DIFF(X,1)=TS(X)*(4/5*((TP(X+2)-TP(X-2))/(TS(X+2)-TS(X-2)))+
    1/5*((TP(X+1)-TP(X-1))/(TS(X+1)-TS(X-1))))
900     NEXT X
910     FOR X= 1 TO LST
920     IF DIFF(X,1)=0     THEN 940
930     GOTO 960
940     DIFF(X,2)=0
950     GOTO 970
960     DIFF(X,2)=DIFF(X,1)*(1+(TS(X)/100))*(1+(TS(X)/200))
970     NEXT X
980 REM
     ** PLOT ROUTINE G(EO)  & F(EO)  %STRAIN VS. T. PRESS.

990 PRINT IN FORM''PLOT OF DIFFERENTIATED CURVE WILL START ON SAME PAPER"/
            "ENTER THE VALUE OF %STRAIN YOU WANT DERIVATIVE CURVE"
            " TO START"/':
1000 INPUT DPT
1010 PRINT "YOU ENTERED ":DPT:" O.K.? ANS. YES OR NO":
1020 INPUT AN$
1030 IF AN$='NO' THEN 990
1040 PRINT;'PLTP'
1050      FOR X=1 TO LST
1060 IF DPT>TS(X) THEN 1120
1070 IF X=1 THEN 1090
1080 IF TS(X)<TS(X-1) THEN 1120
1090      DPLT=ROUND((TS(X)-XMIN)*H)
1100      PRINT IN FORM'4%B4%/30(C127)':DPLT,ROUND((DIFF(X,1)-YMIN)*V)
1110      PRINT IN FORM'4%B4%/30(C127)':DPLT,ROUND((DIFF(X,2)-YMIN)*V)
1120      NEXT X
1130 PRINT 'PLTT'!


1140 REM

      ** PLOT-  %STRAIN VS. T.P. & E.P. **


1150 PRINT IN FORM'/"PLOT OF % STRAIN VS. TOTAL PRESSURE AND EFFECTIVE"/
       5B"PRESSURE ...CHANGE LINEAR PAPER...TYPE CONTINUE"/':
1160 PAUSE
1170 PRINT IN FORM'/"PLOT %STRAIN (XAXIS) VS. TOTAL AND EFFECTIVE"/
       5B"PRESSURES (YXIS)"/5B"ENTER  XMIN,XMAX,YMIN,YMAX"/':
1180 INPUT XMIN,XMAX,YMIN,YMAX
1190 DO 730
1200 DO 670:680
1210 INPUT AN$
1220 IF AN$='NO' THEN 1170
1230 PRINT;'PLTP'
1240 FOR I=1 TO NUM
1250 DO 760
1260 PRINT IN FORM'4%B4%/30(C127)':ROUND((TS(I)-XMIN)*H),
      ROUND((EP(I)-YMIN)*V)
1270 NEXT I
1280 PRINT;'PLTT'
1290 REM
```

** PLOT ROUTINE FOR LN(DELTA-V/V) **

```
1300 PRINT IN FORM'5B"PLOT LN(DELTA-V/V)(X AXIS) VS. TOTAL PRESSURE(Y AXIS)"/
          "ENTER RANGE LIMITS FOR LN(DELTA-V/V) & TOTAL PRESS.:"/
          "..ENTER XMIN,XMAX,YMIN,YMAX"/':
1310 INPUT XMIN,XMAX,YMIN,YMAX
1320 H=9999/(XMAX-XMIN),V=9999/(YMAX-YMIN)
1330 DO 670:690
1340 IF AN$='NO' THEN 1300
1350 PRINT;'CHANGE LINEAR (10X 10 ) PAPER FOR LN PLOT- TYPE CONT.'
1360 PAUSE
1370 PRINT;'PLTP'
1380   FOR I=1 TO NUM
1390   PRINT IN FORM'4%B4%/30(C127)':ROUND((LOG(ABS(VOL(I,3)))-XMIN)*H),
           ROUND((TP(I)-YMIN)*V)
1400   NEXT I
1410 PRINT 'PLTT'
1420 REM
      ** PLOT ROUTINE FOR LOG10(DELTA-V/V) ON SEMI-LOG**
1430 PRINT IN FORM'/"PLOT OF LOG10(DELTA-V/V) IS NEXT-CHANGE TO"/
        B"EITHER 2 OR 3-CYCLE SEMI-LOG PAPER, THEN TYPE CONTINUE"//':
1440 PAUSE
1450 PRINT IN FORM'/"WHICH ARE YOU USING? 2 OR 3...ENTER :"/':
1460 INPUT SLOG
1470 IF SLOG<2 OR SLOG>3 THEN 1450
1480 FOR X=1 TO NUM
1490 VOL(X,6)=(VOL(X,5)/SLOG*9999)+10000
1500 NEXT X
1510 PRINT;'PLTP'
1520   FOR I=1 TO NUM
1530   PRINT IN FORM'#B#/30(C127)':INT(VOL(I,6)),ROUND((TP(I)-YMIN)*V)
1540   NEXT I
1550 PRINT;'PLTT'
1560 END
1570 PAGE=PAGE+1
1580 LF=70-LF
1590 DO 230:250
1600 PRINT IN FORM'60B5%B2%//':PAG$,PAGE
1610 DO 530
1620 DO 550:560
1630 LF=14
1640 RETURN
>
```

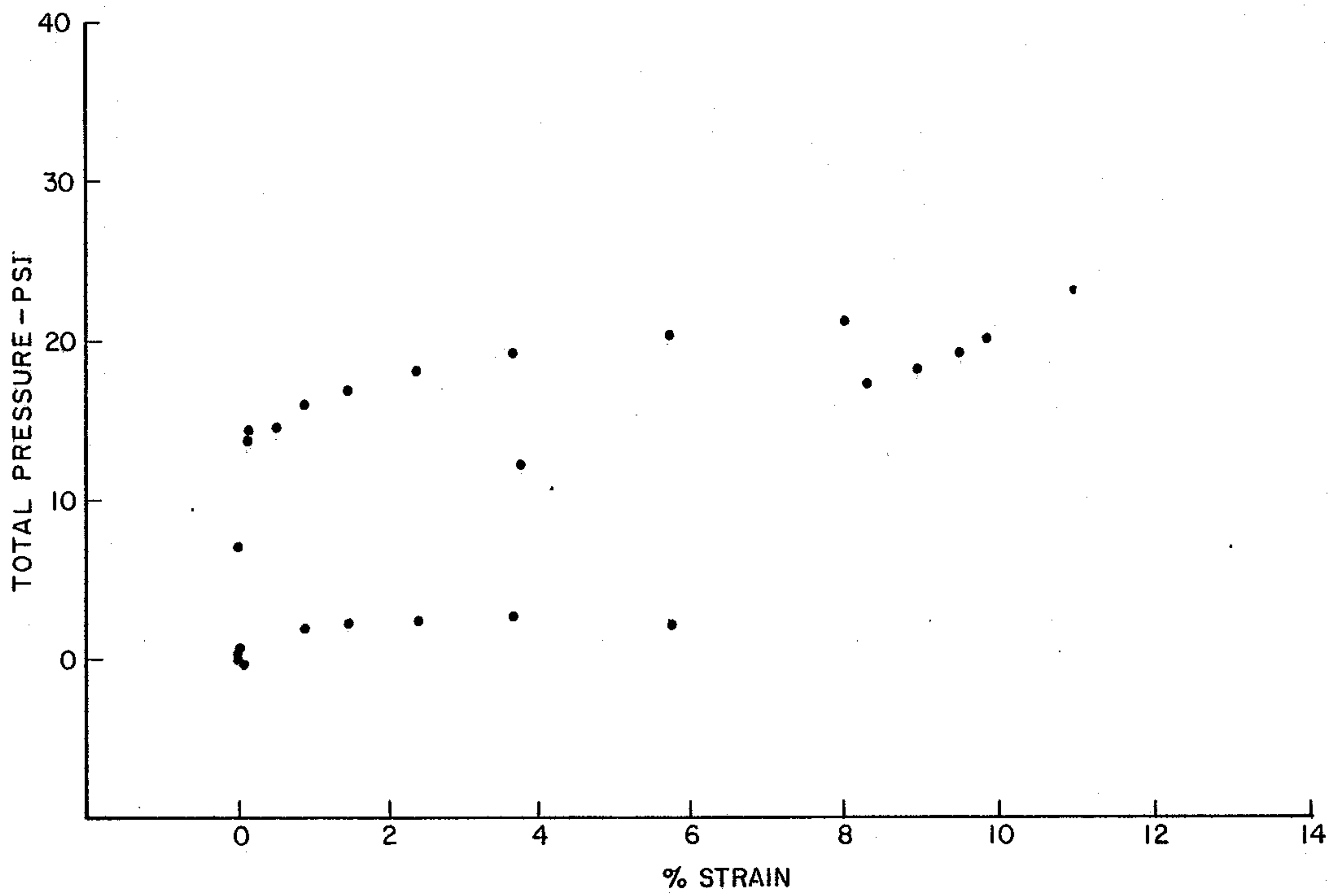


FIGURE 16, TP VS ξ & DERIVED TP [F(EO) & G(EO)]

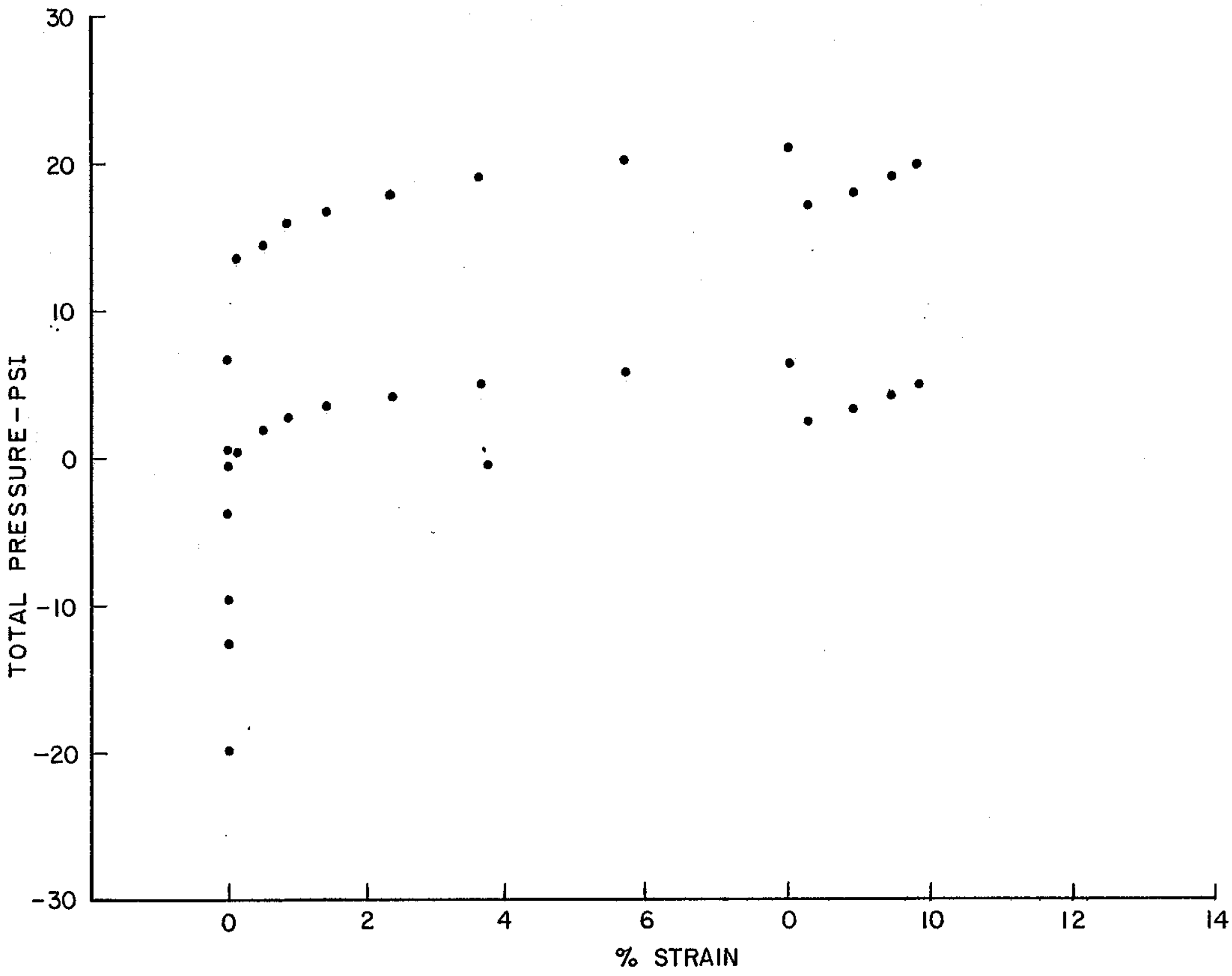


FIGURE 17, TP & EP VS % ξ

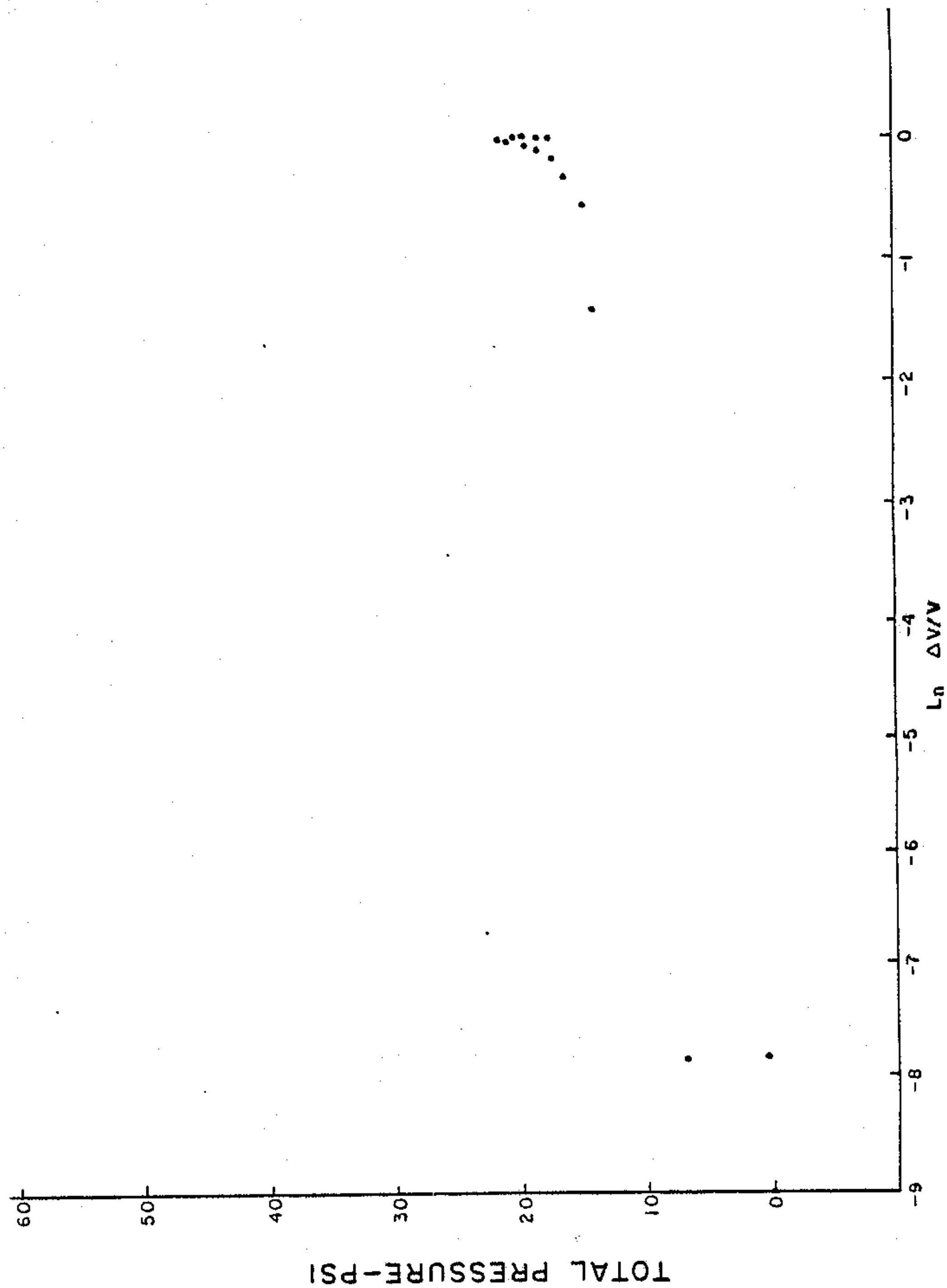


FIGURE 18. T P VS Ln ΔV/V

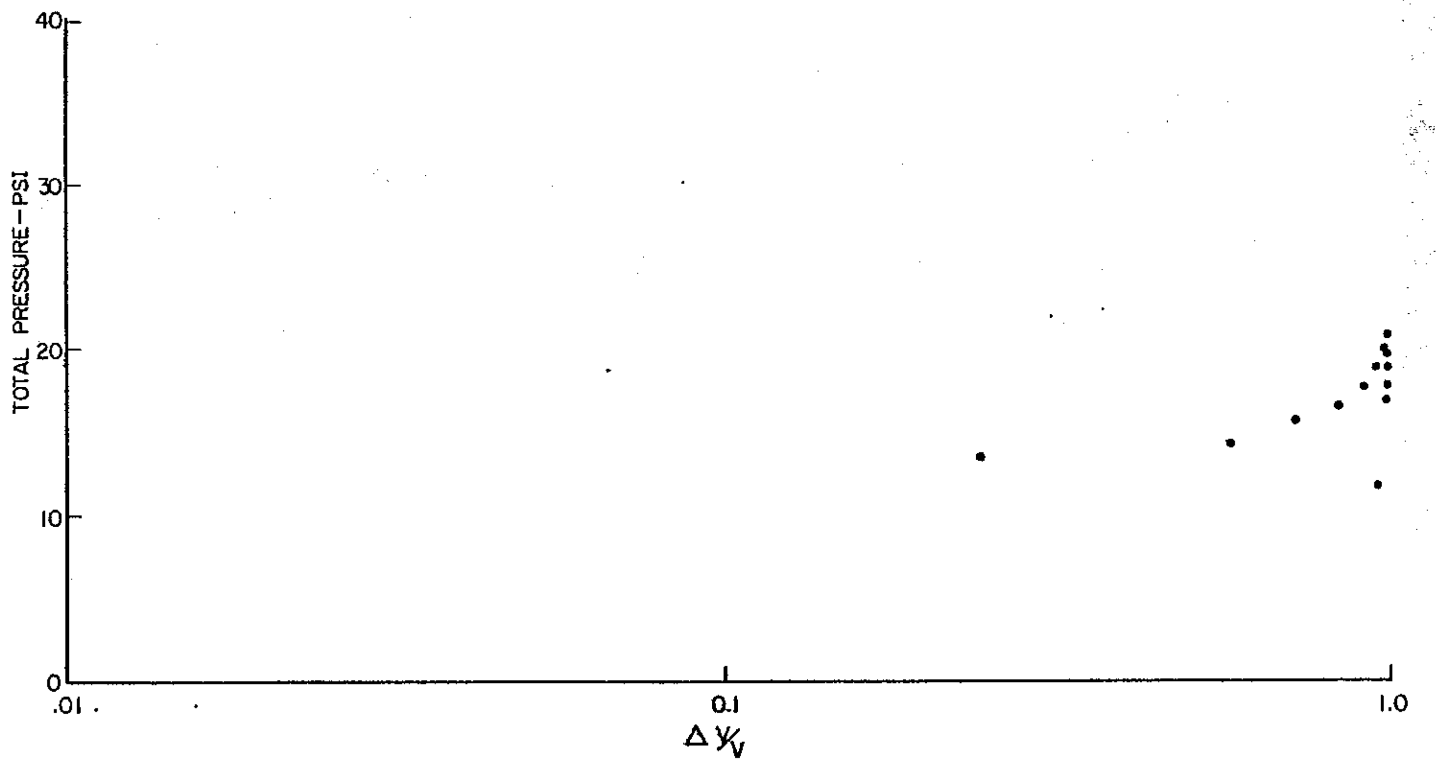


FIGURE 19, TP VS ΔV/V